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United States Patent [19] Chitayat

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[54] **CLOSED-PATH LINEAR MOTOR**

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[*] Notice: This patent is subject to a terminal disclaimer.

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[22] Filed: **Apr. 29, 1998**

Related U.S. Application Data

[63] Continuation-in-part of application No. 09/031,009, Feb. 26, 1998, application No. 09/031,287, Feb. 26, 1998, Pat. No. 5,907,200, application No. 09/040,132, Mar. 17, 1998, and application No. 09/055,573, Apr. 6, 1998.

[51] **Int. Cl.⁶** **H02K 41/00**

[52] **U.S. Cl.** **310/12; 318/135**

[58] **Field of Search** 310/12, 13, 14;
318/135

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,825,111 4/1989 Hommes et al. 310/12

Primary Examiner—Nestor Ramirez

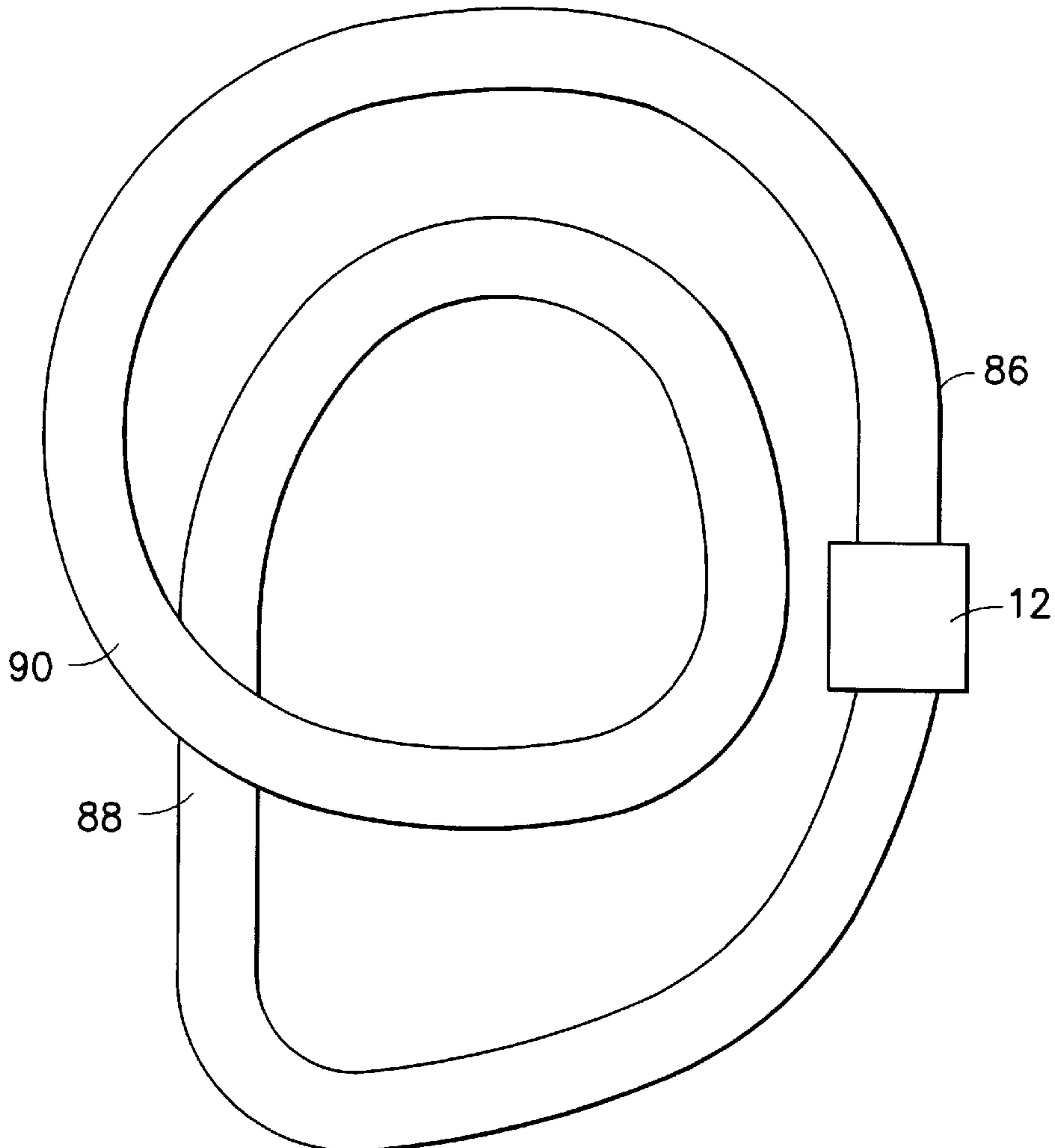
Assistant Examiner—Judson H. Jones

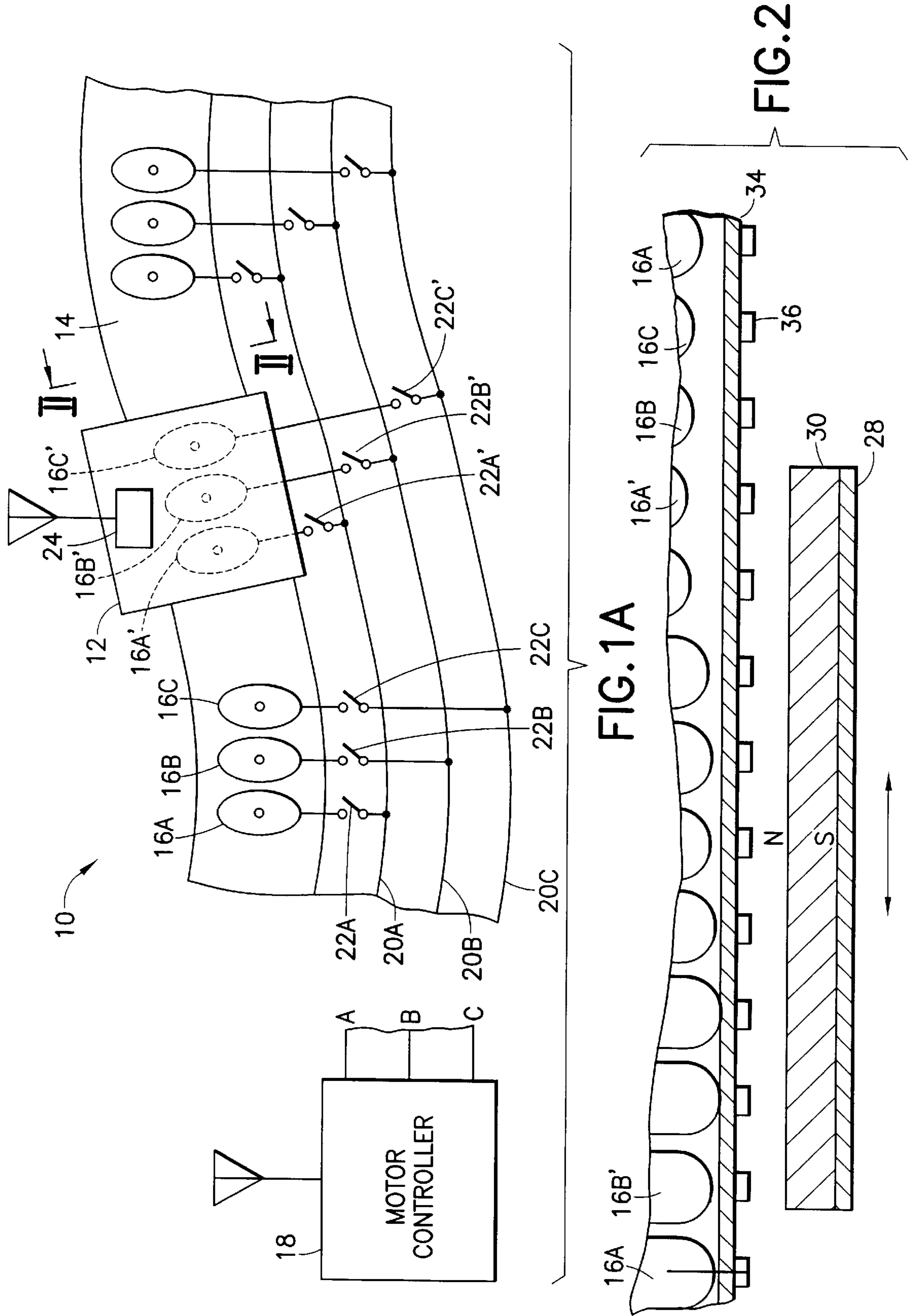
Attorney, Agent, or Firm—John M. Miller; John J. Horn

[57] **ABSTRACT**

A linear motor path forms a closed figure. Contactless power control and position feedback permit a linear motor stage to traverse the closed figure without interference from trailing wires. One embodiment of the closed figure includes a racetrack pattern with straight runs joined by curved ends. Axes of armature windings are skewed to lie across the path in the curved ends to maintain force on the linear motor stage. Other embodiments of the invention includes multi-level paths wherein one portion of the path crosses over another portion of the path. Disclosure is made of a linear motor stage supported below the path by magnetic attraction between permanent magnets on the stage and magnetic material in the path.

8 Claims, 18 Drawing Sheets





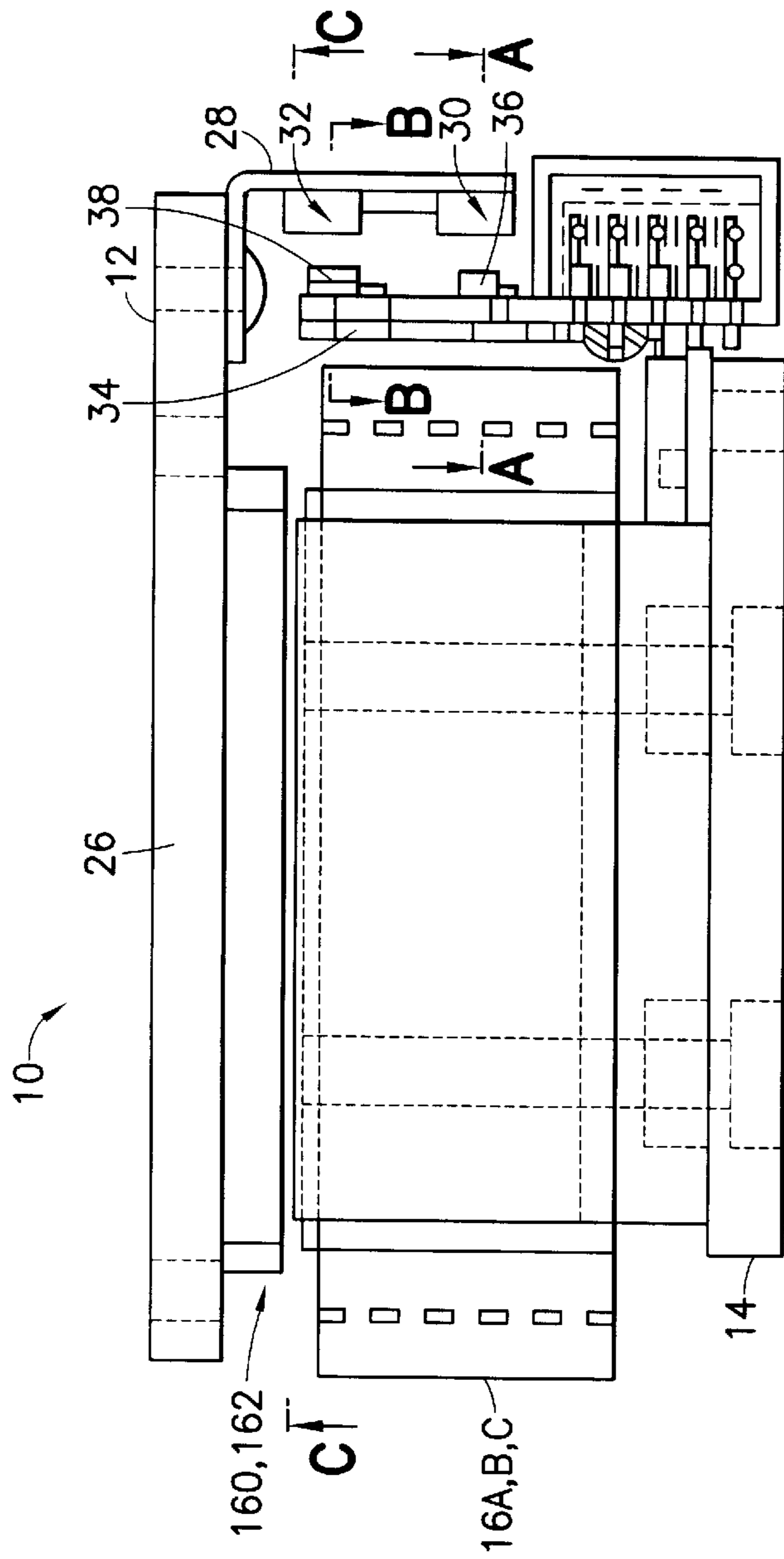


FIG. 1B

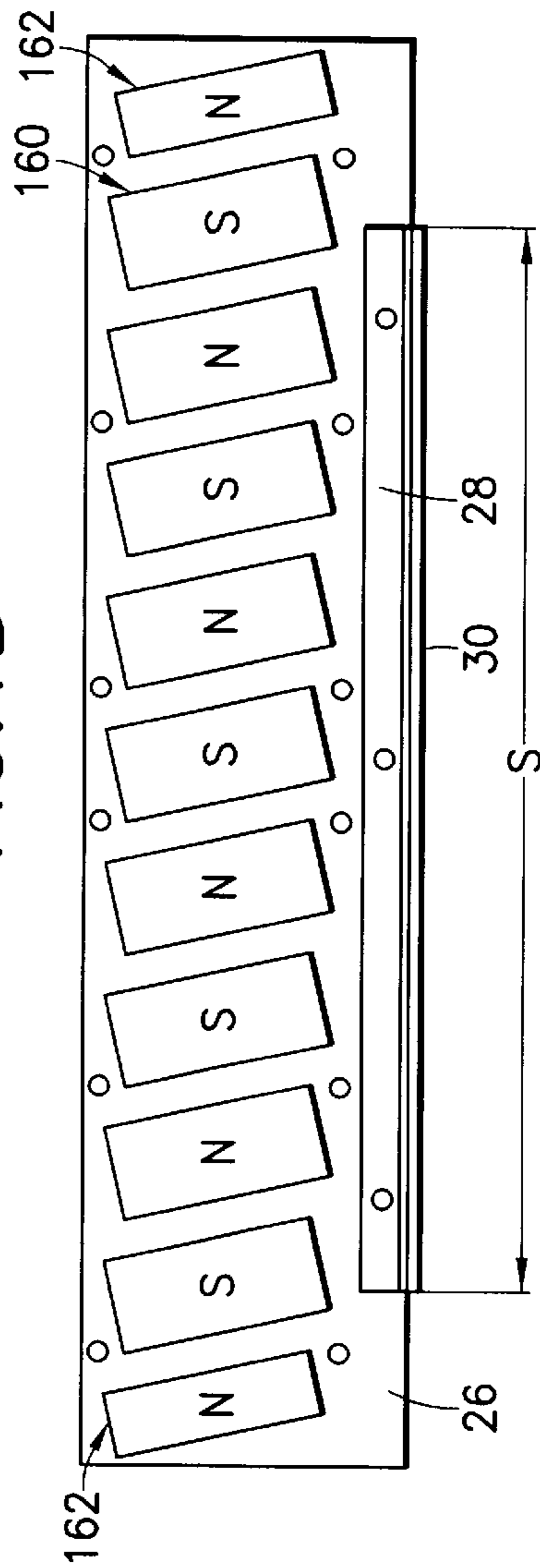


FIG. 3

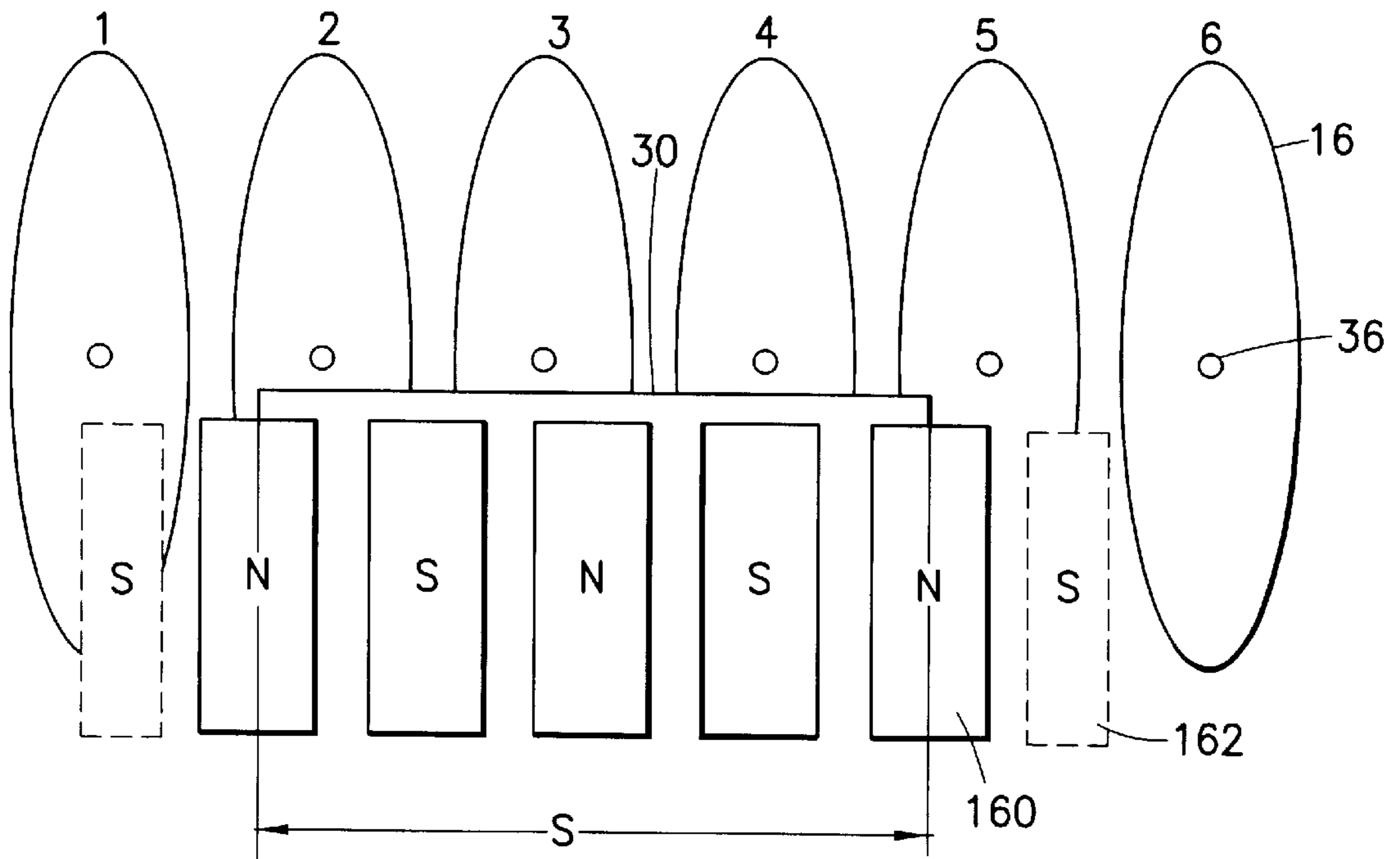


FIG.3A

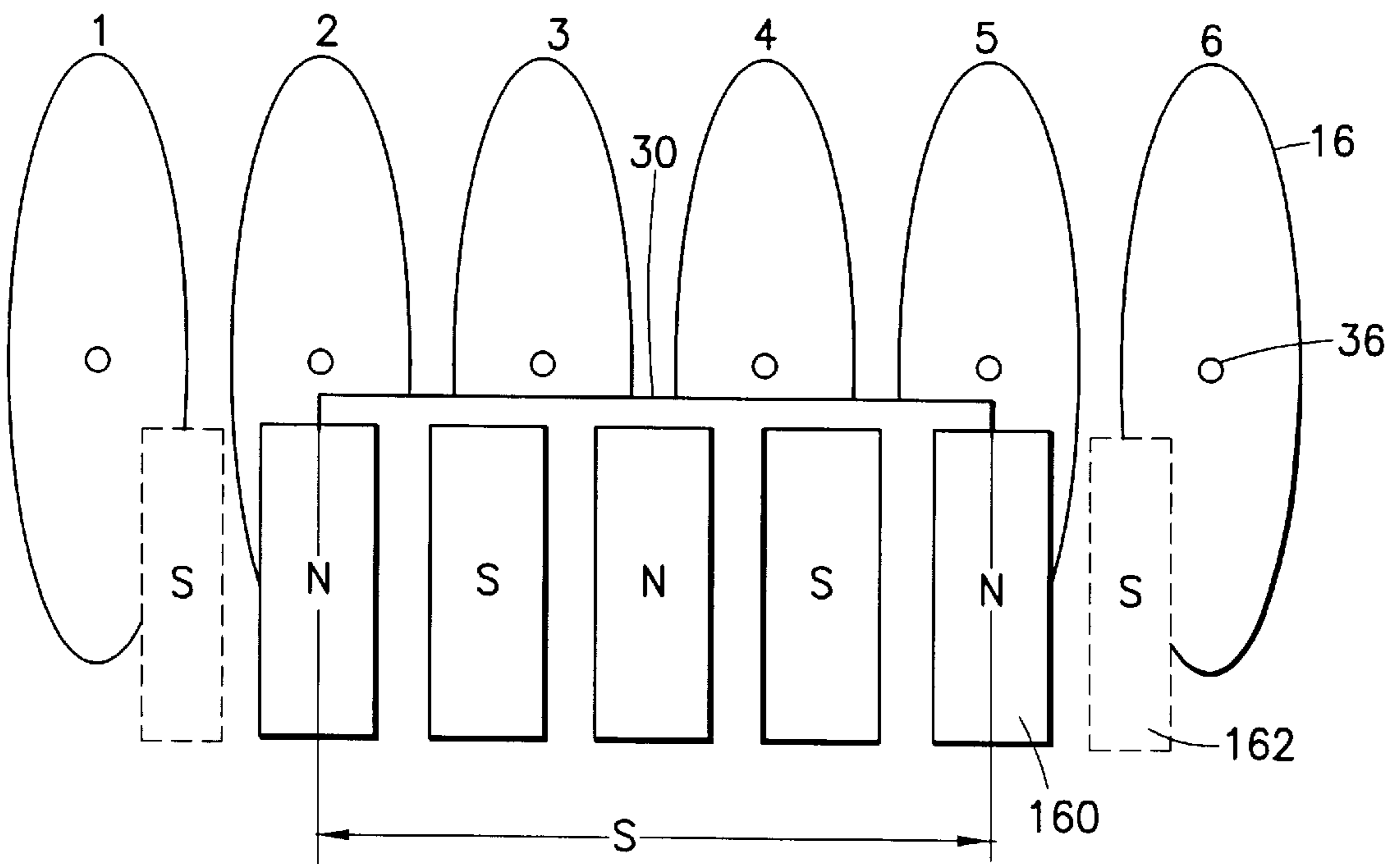


FIG.3B

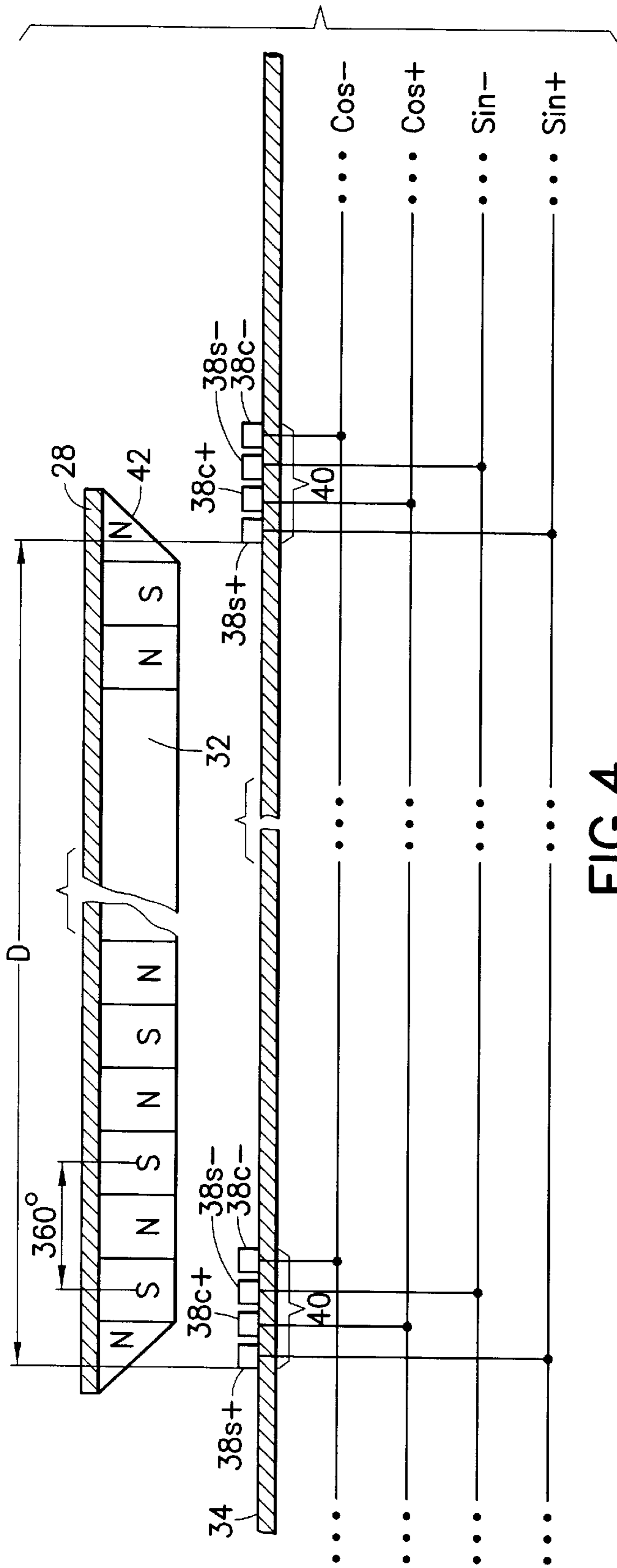


FIG. 4

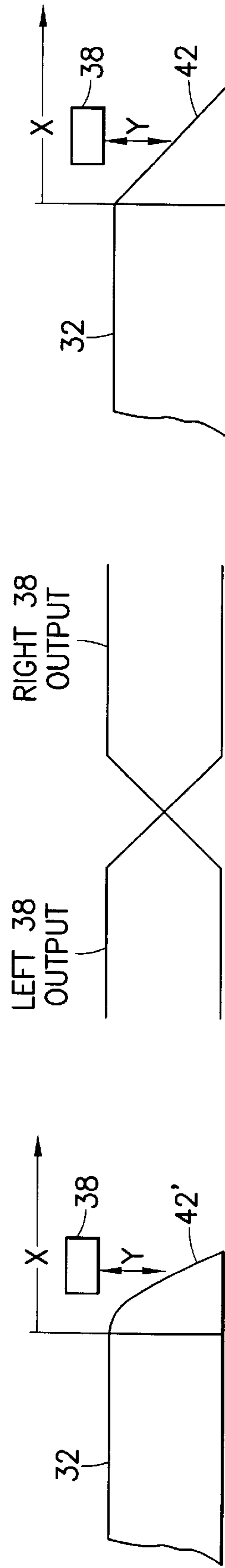


FIG. 4A

FIG. 4B

FIG. 4C

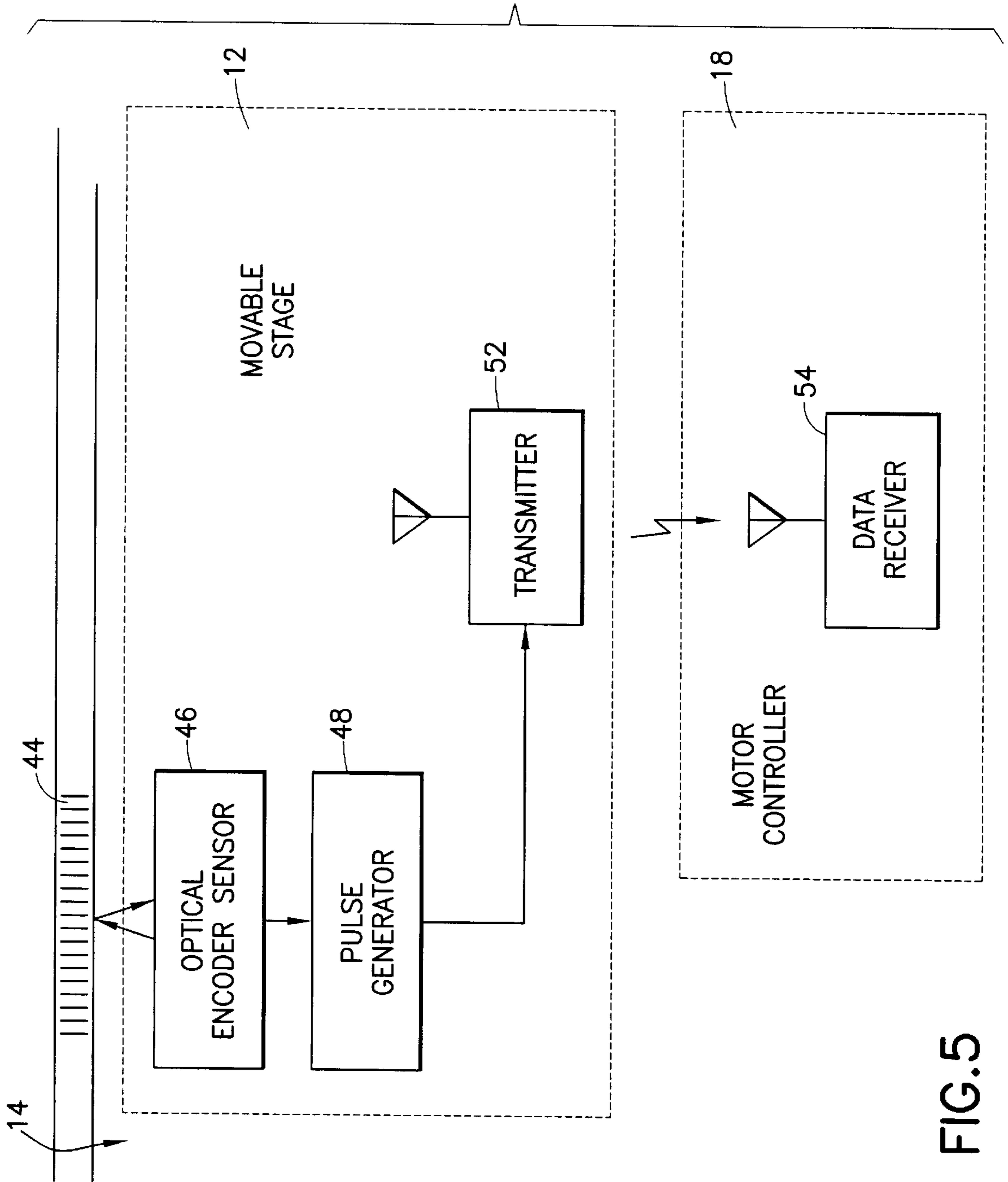


FIG. 5

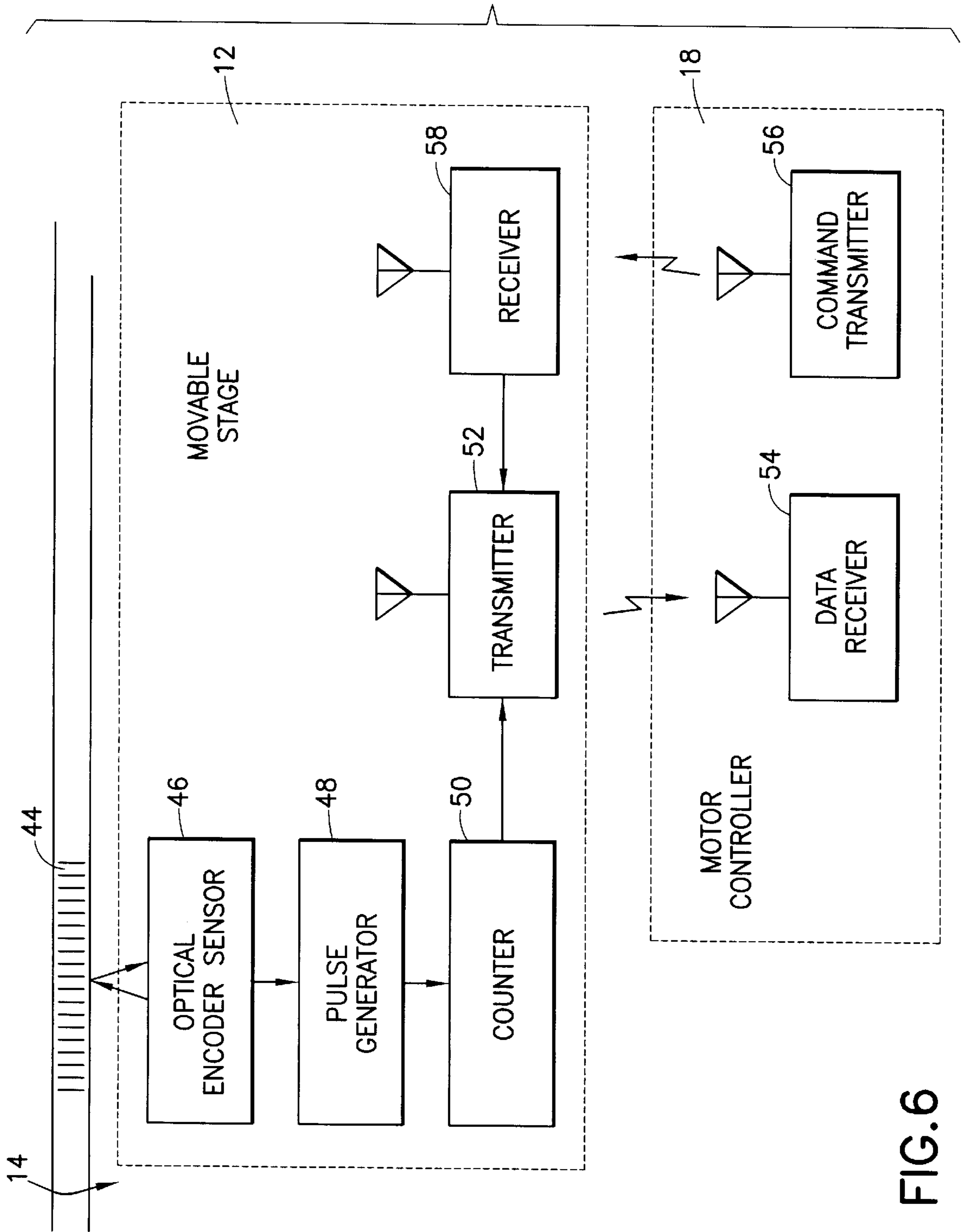


FIG. 6

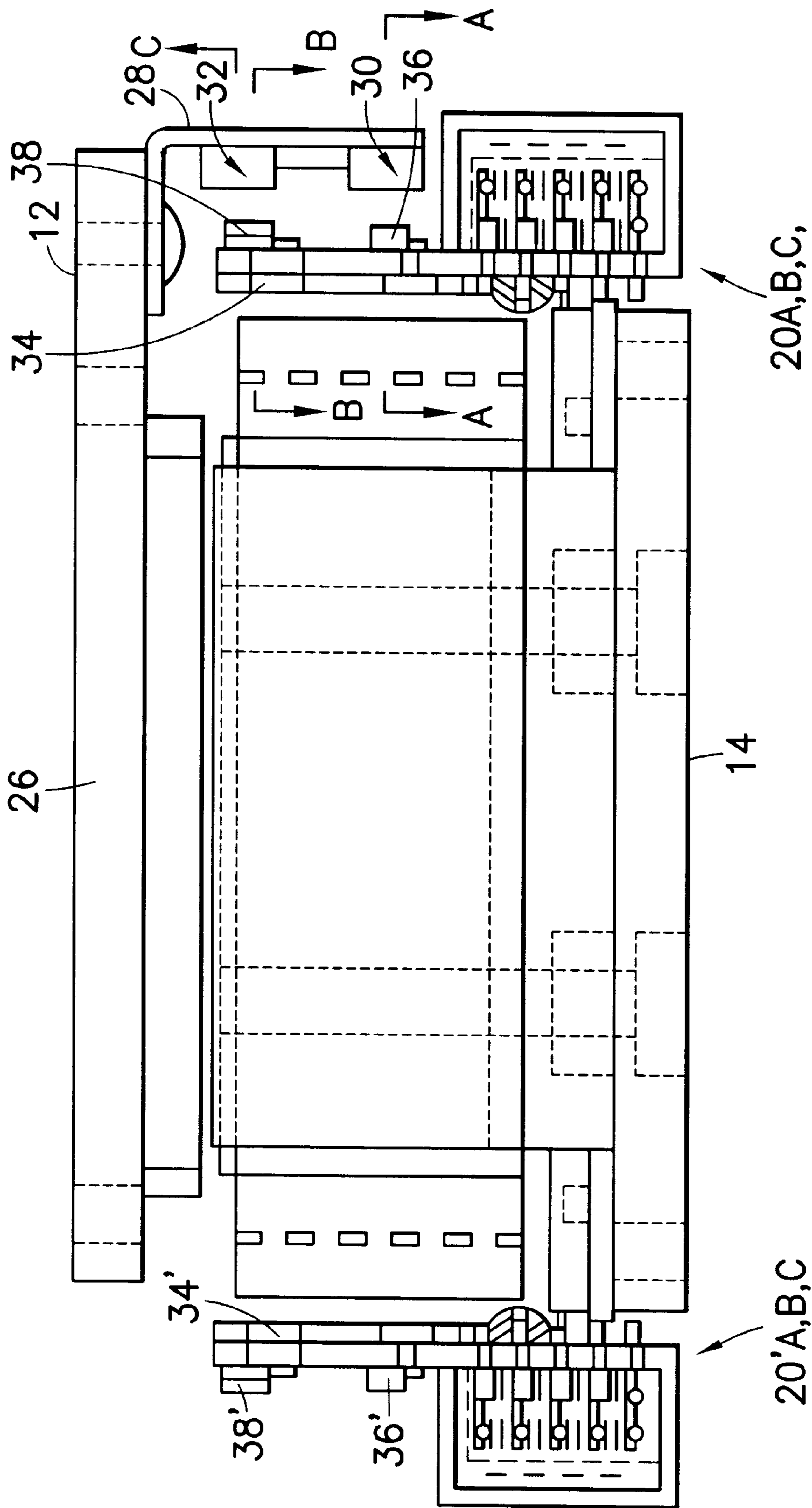


FIG. 7

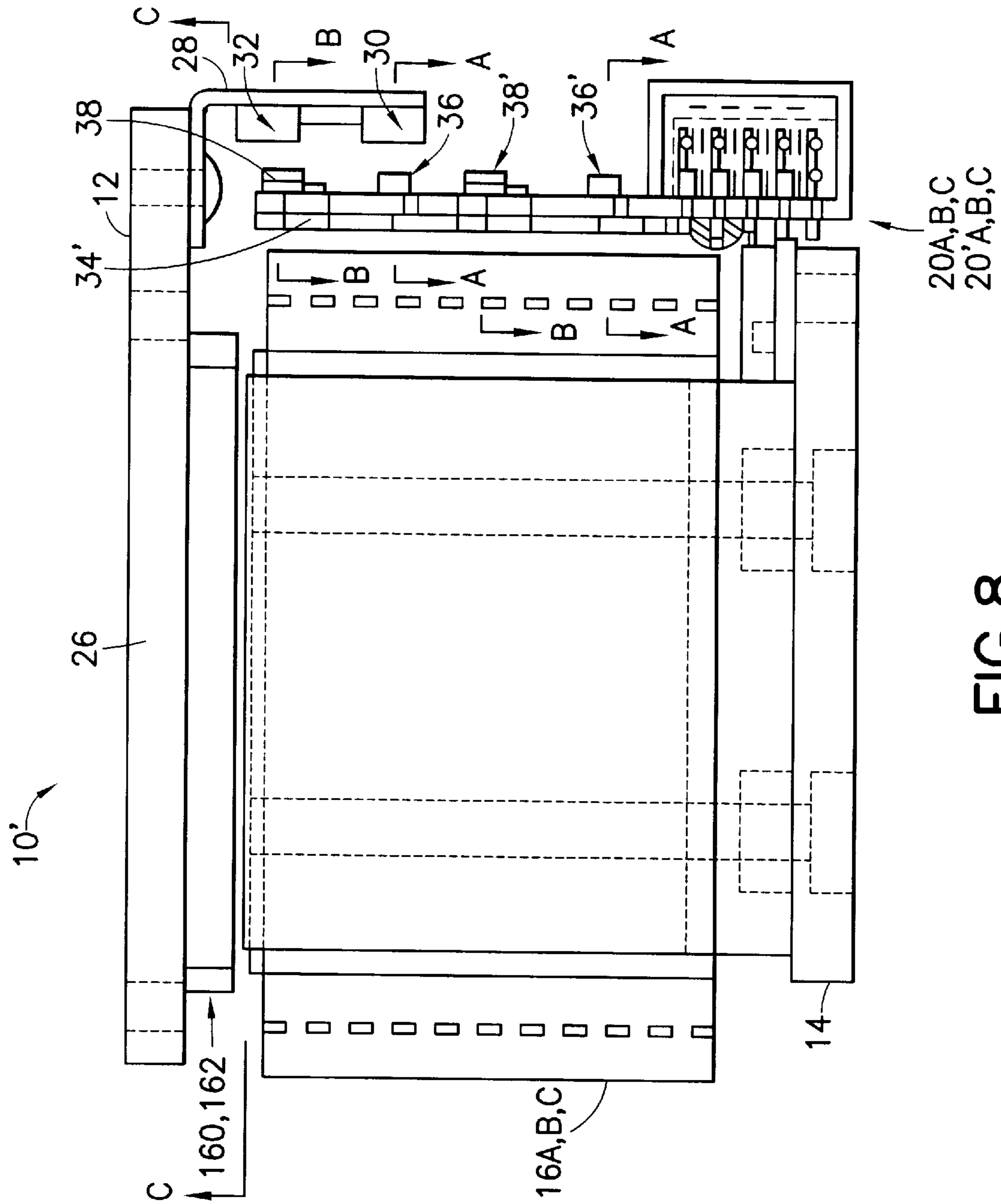


FIG. 8

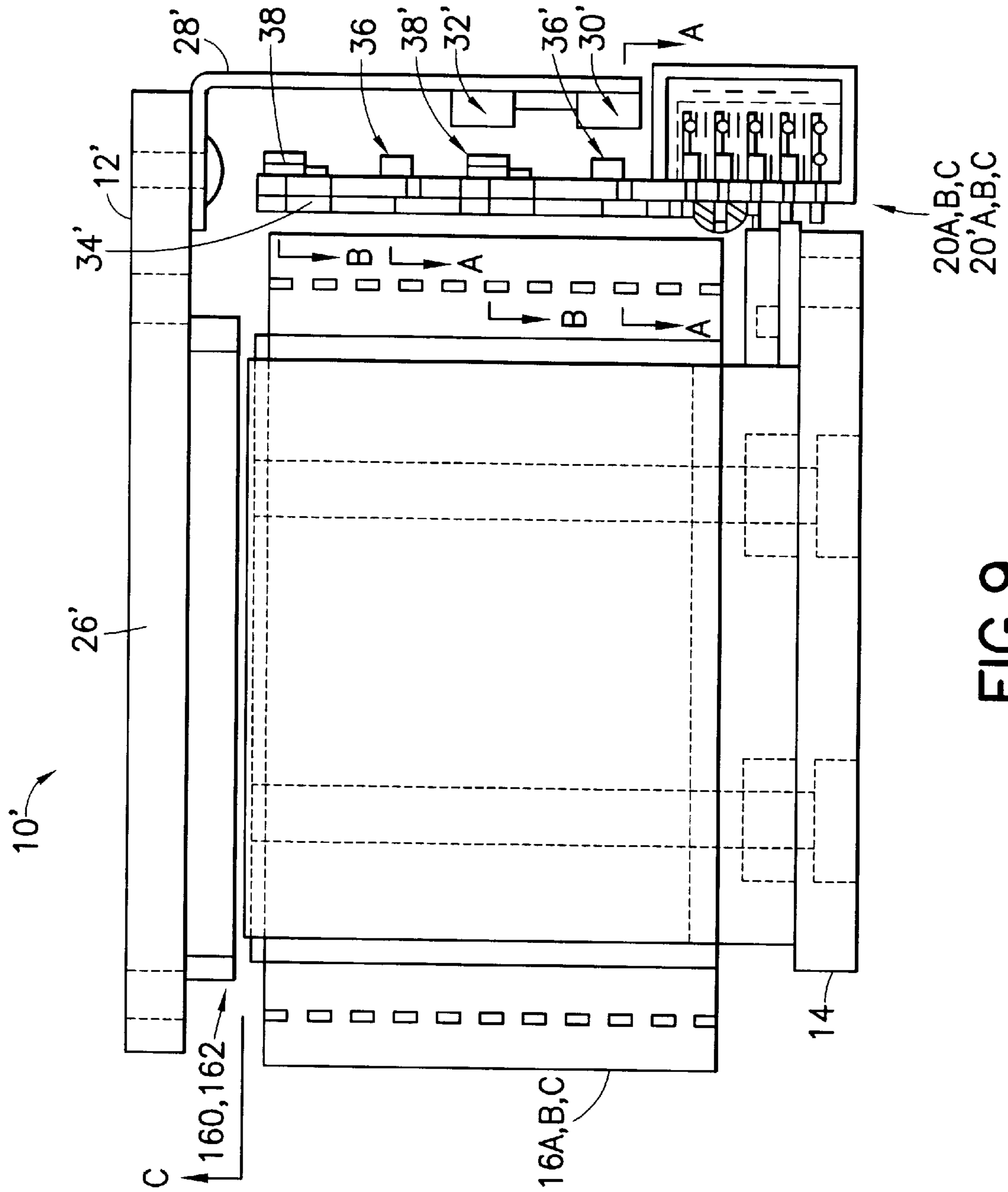


FIG. 9

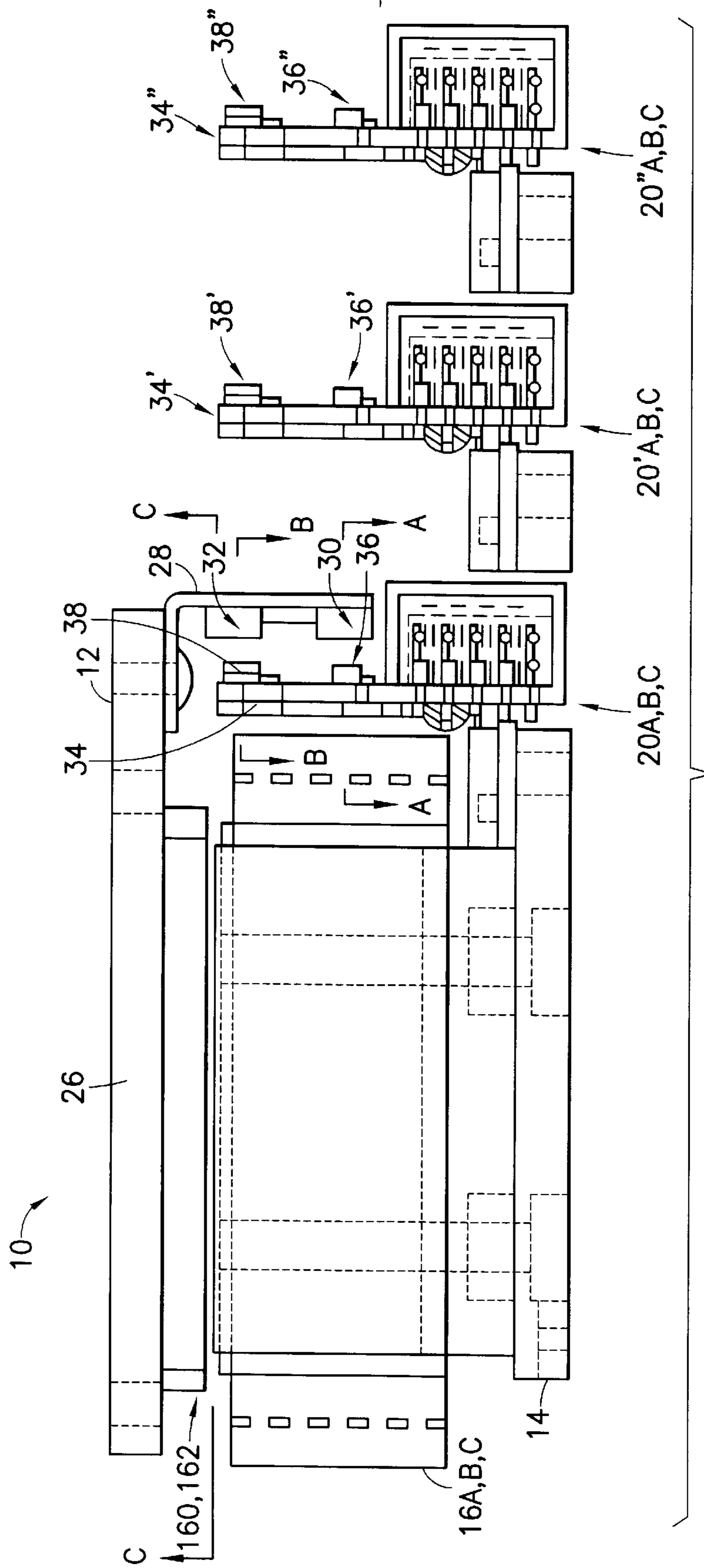


FIG. 10

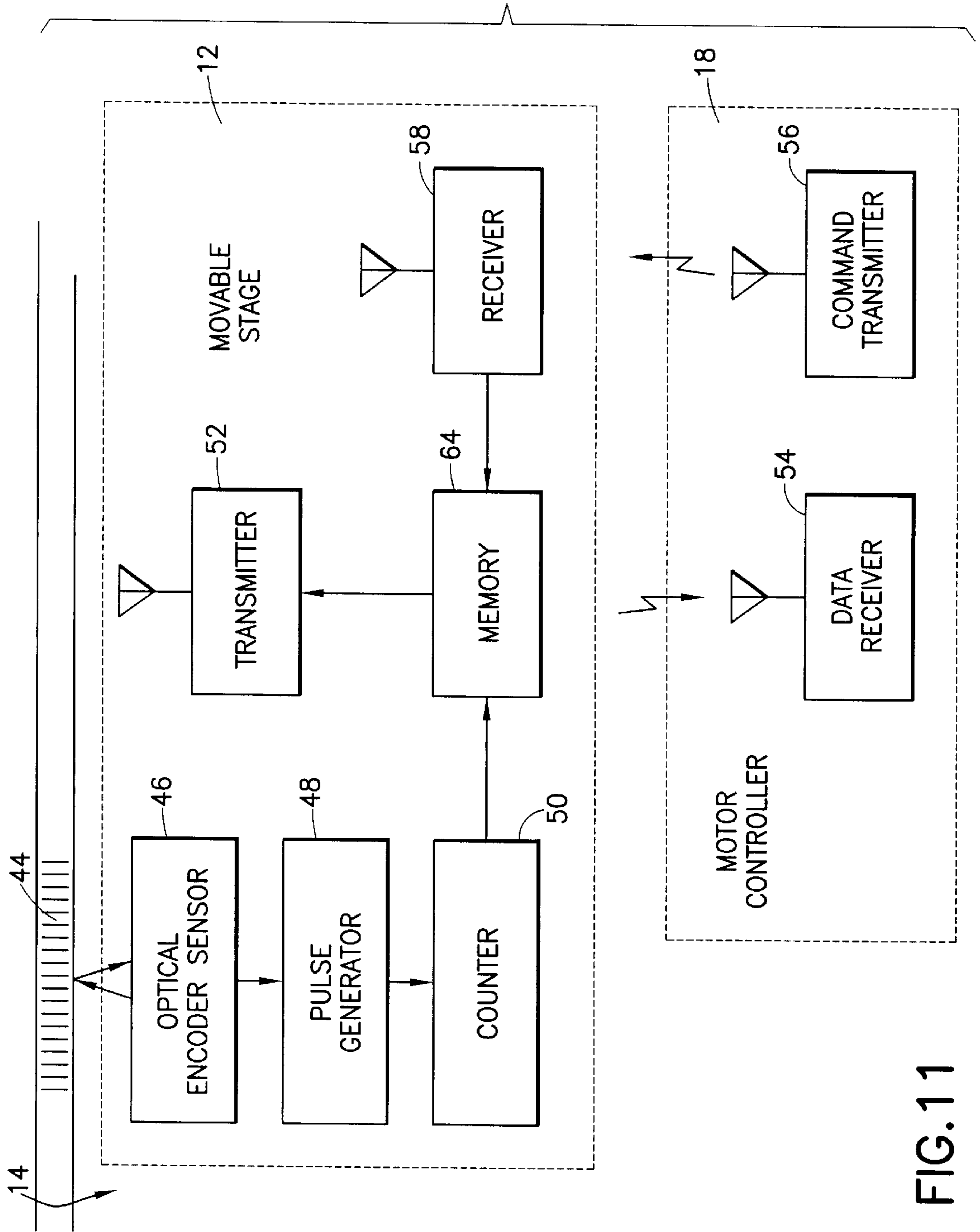
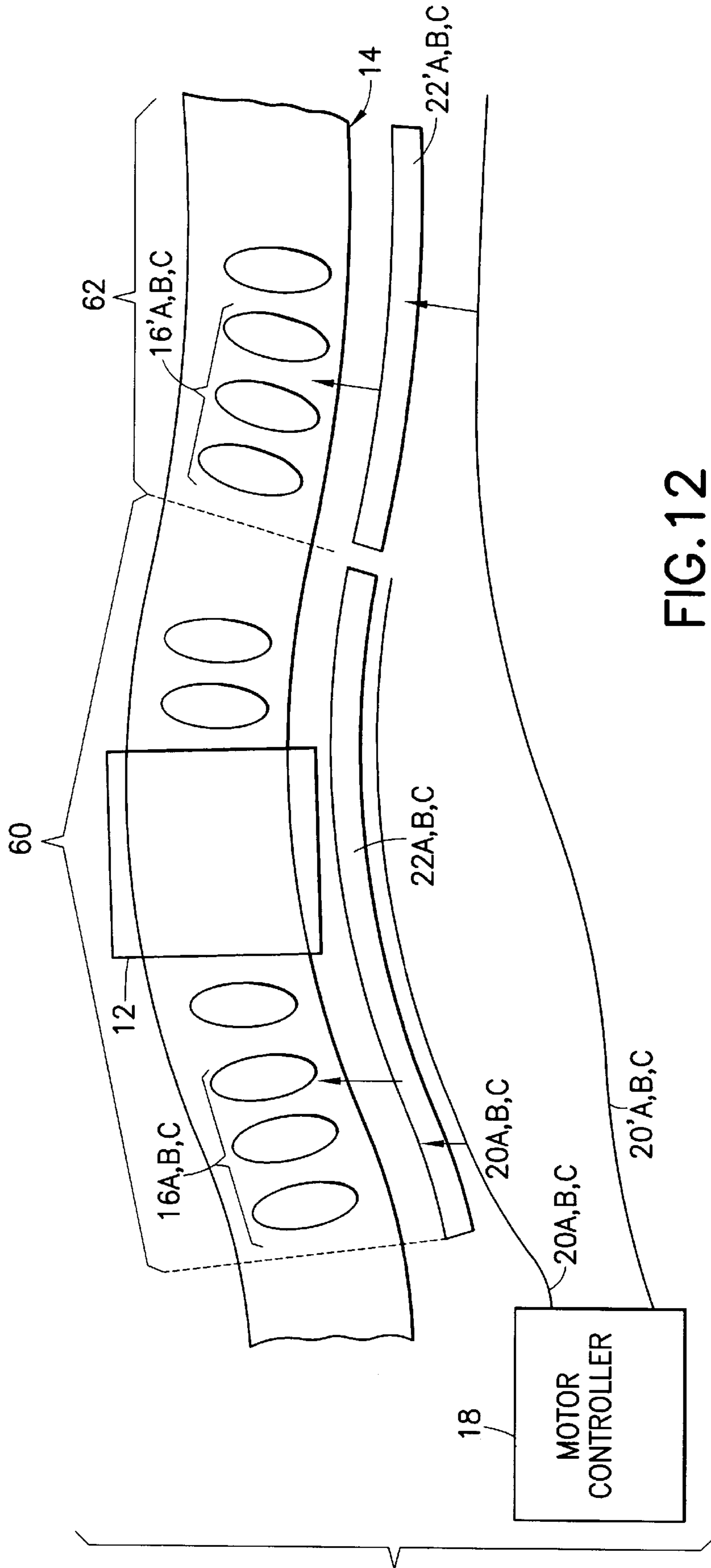


FIG. 11



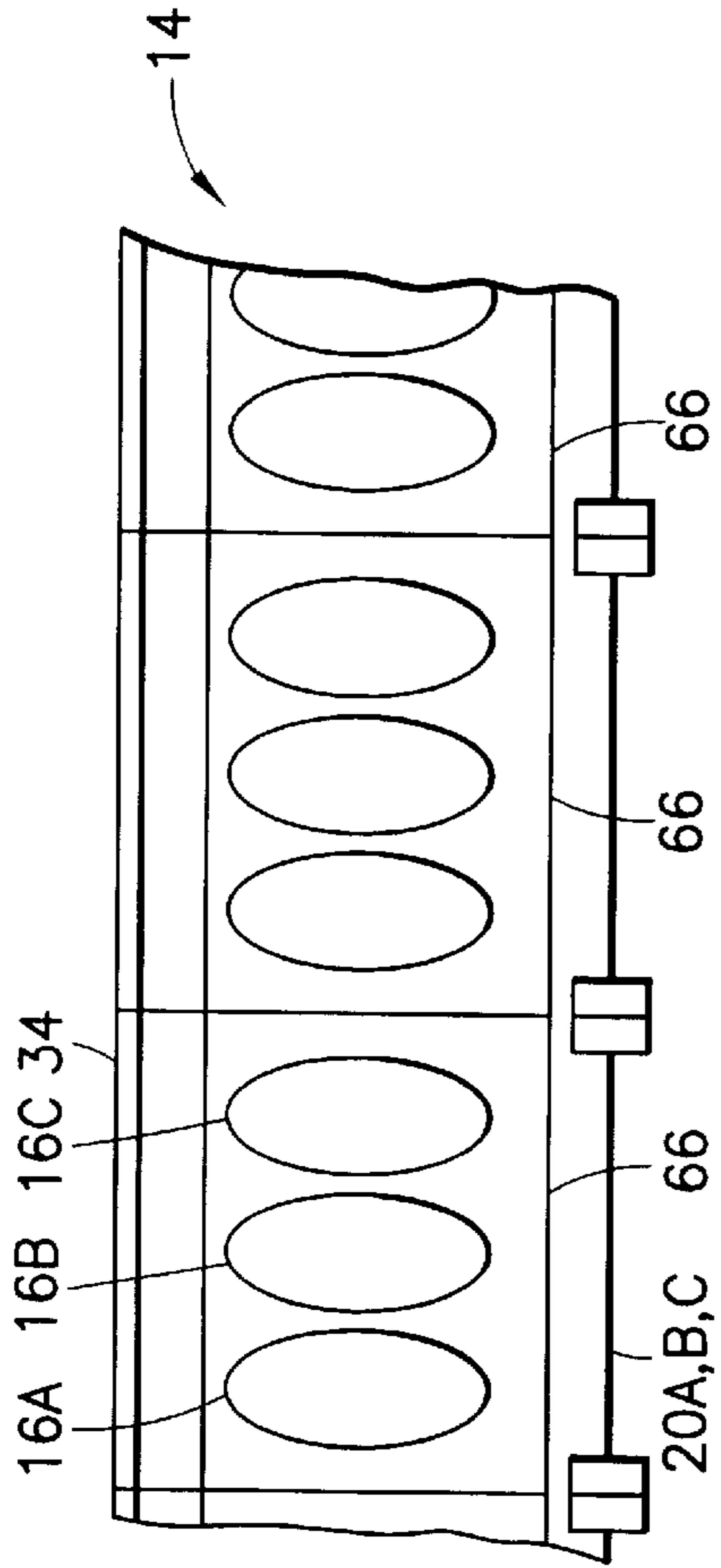


FIG. 13

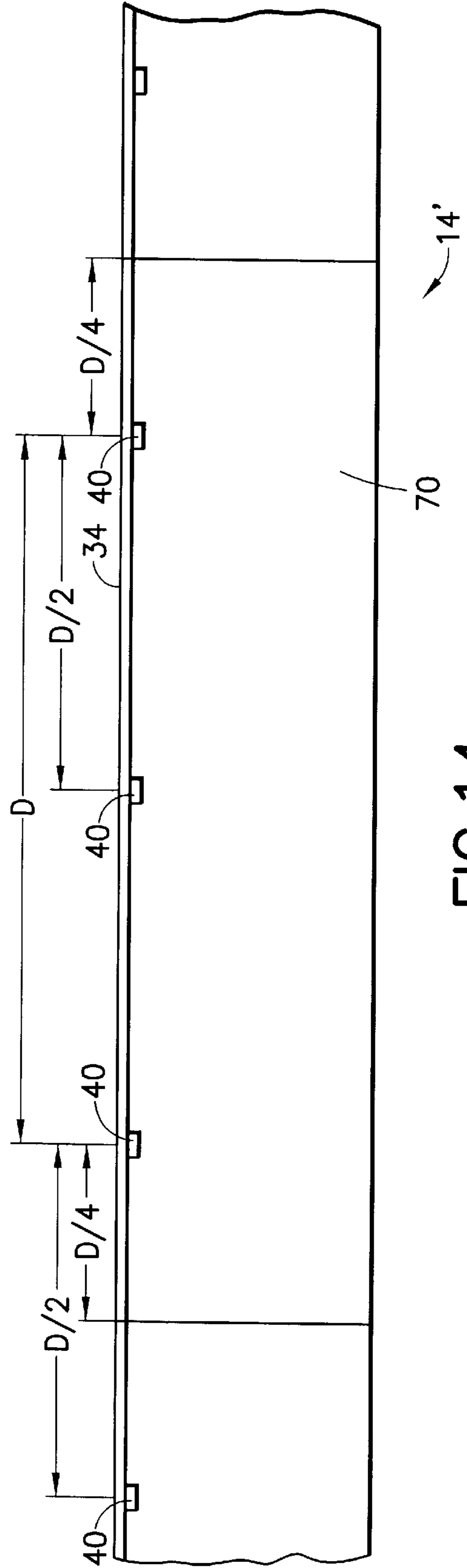


FIG. 14

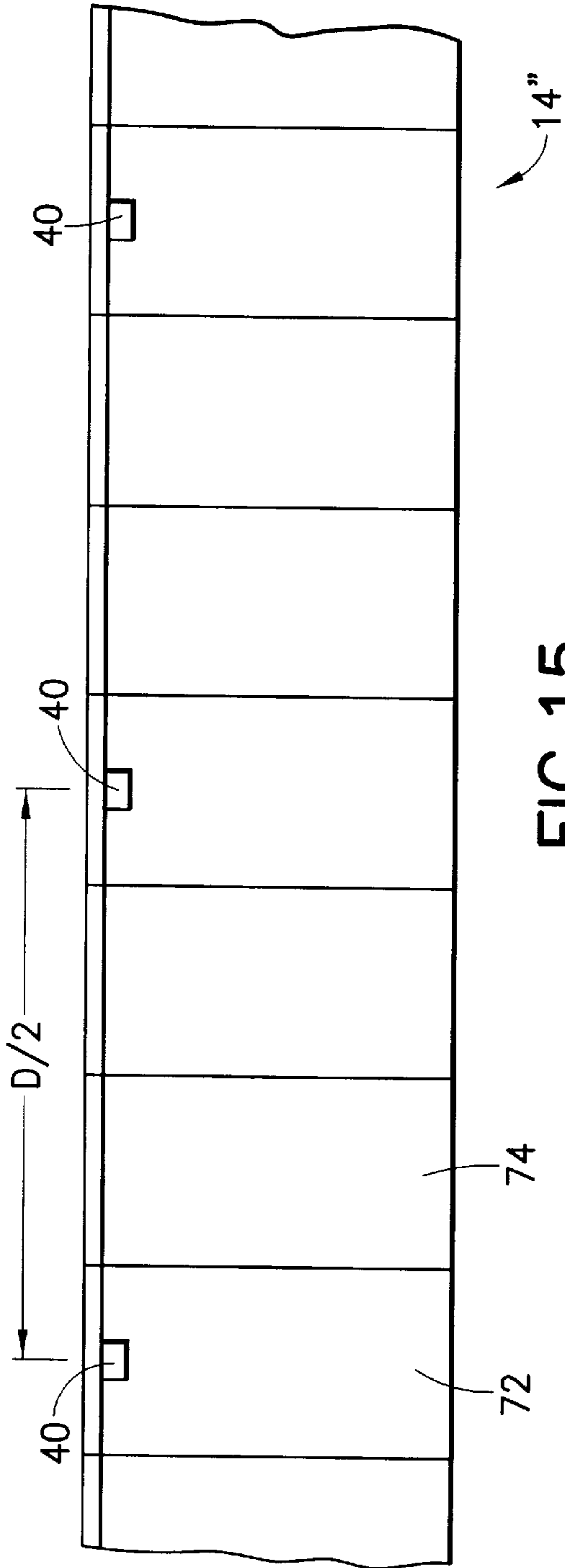


FIG. 15

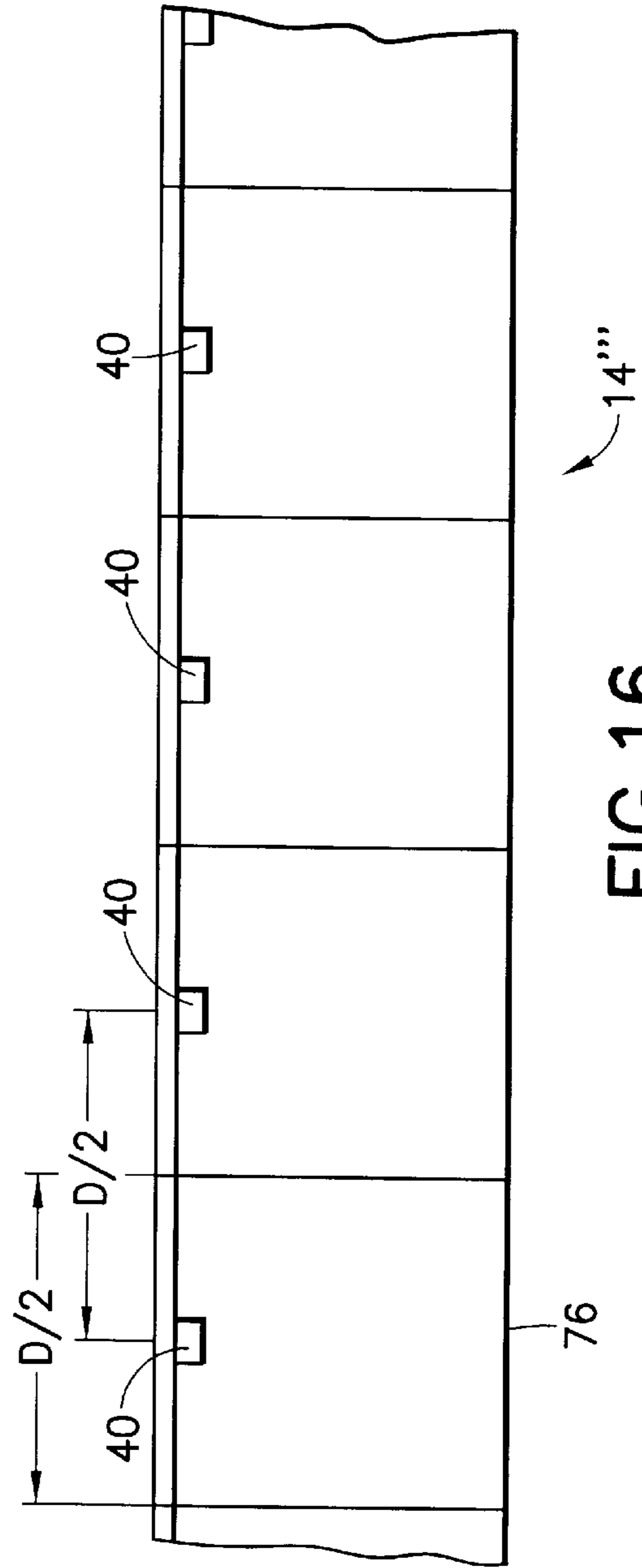
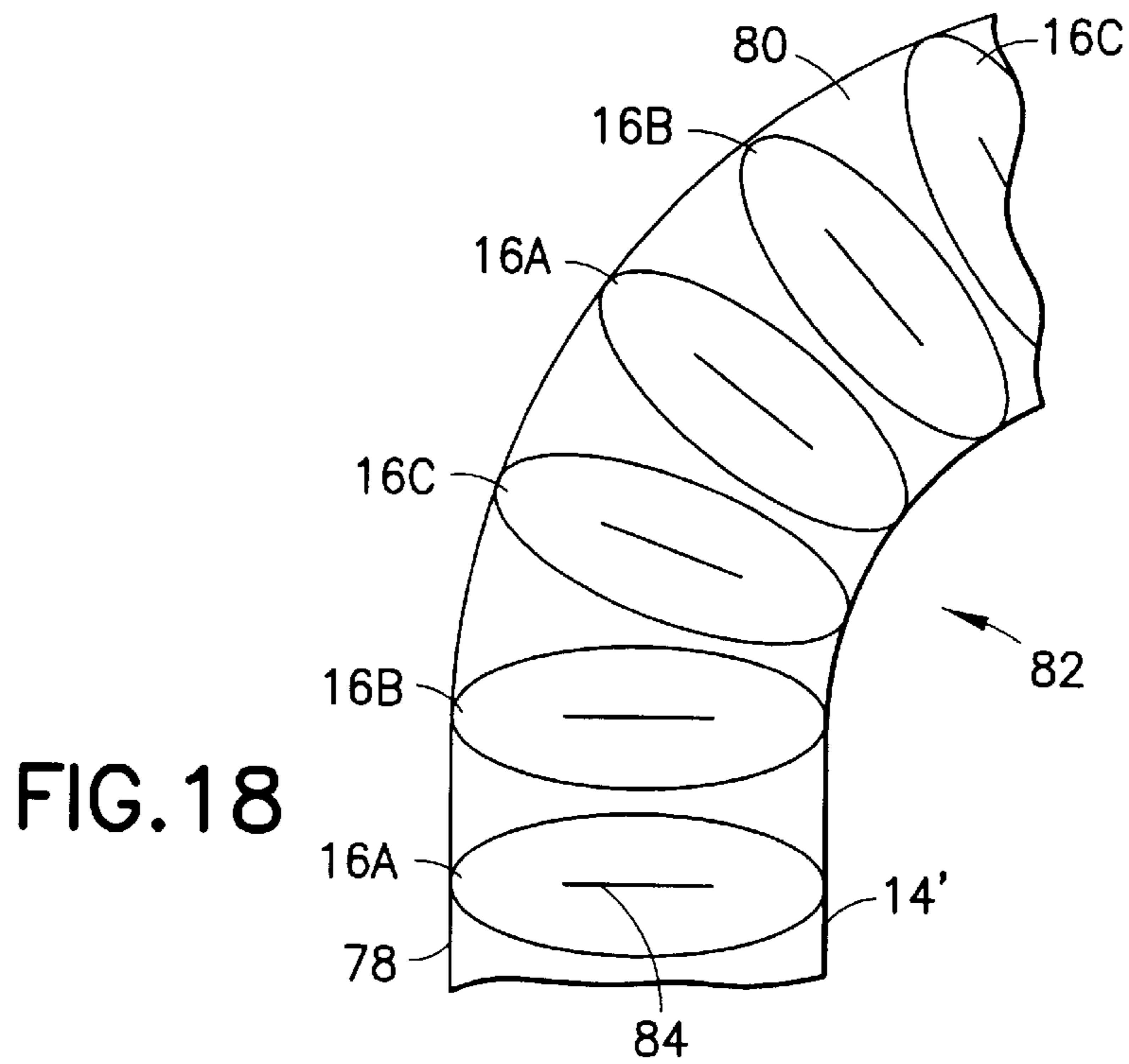
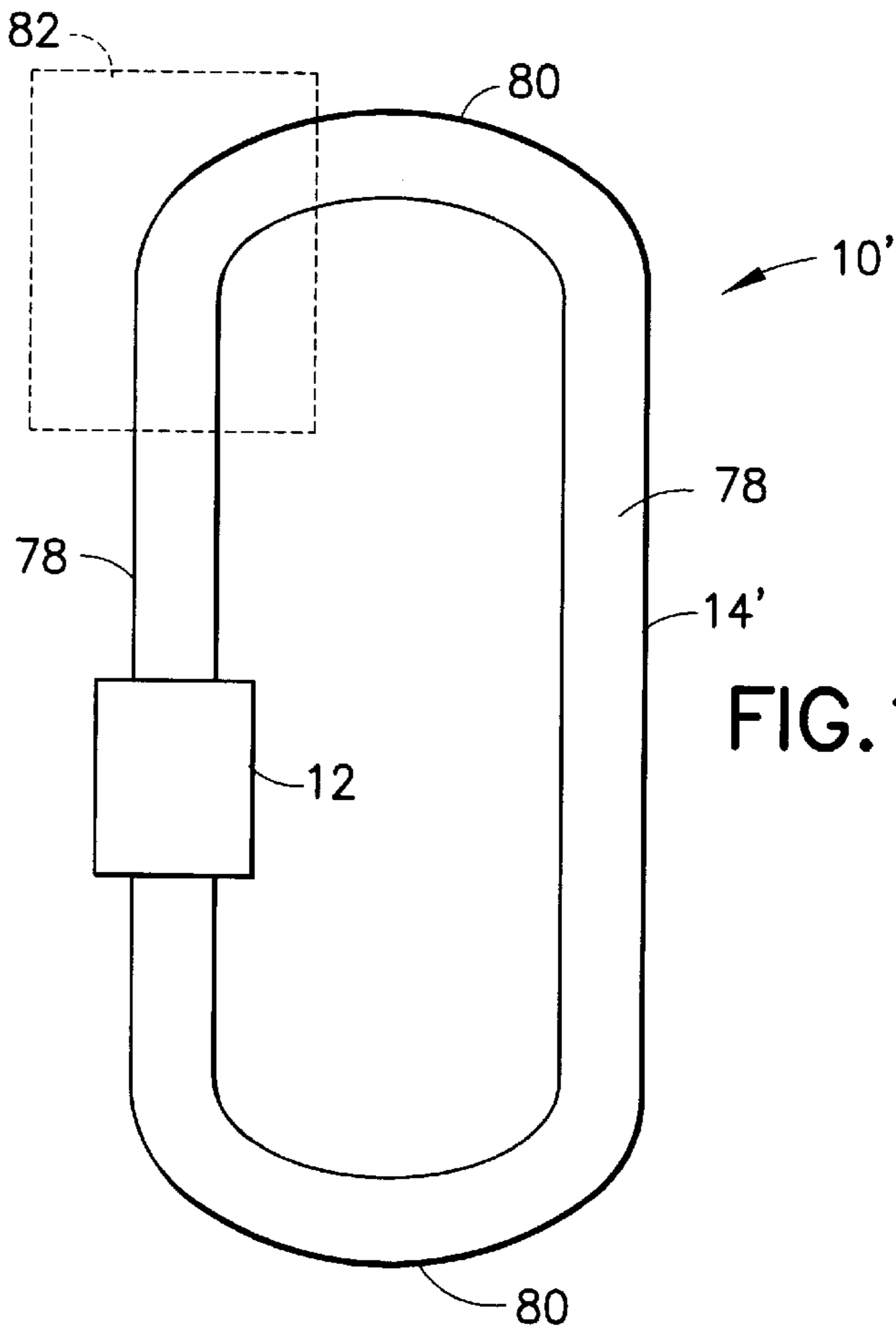


FIG. 16



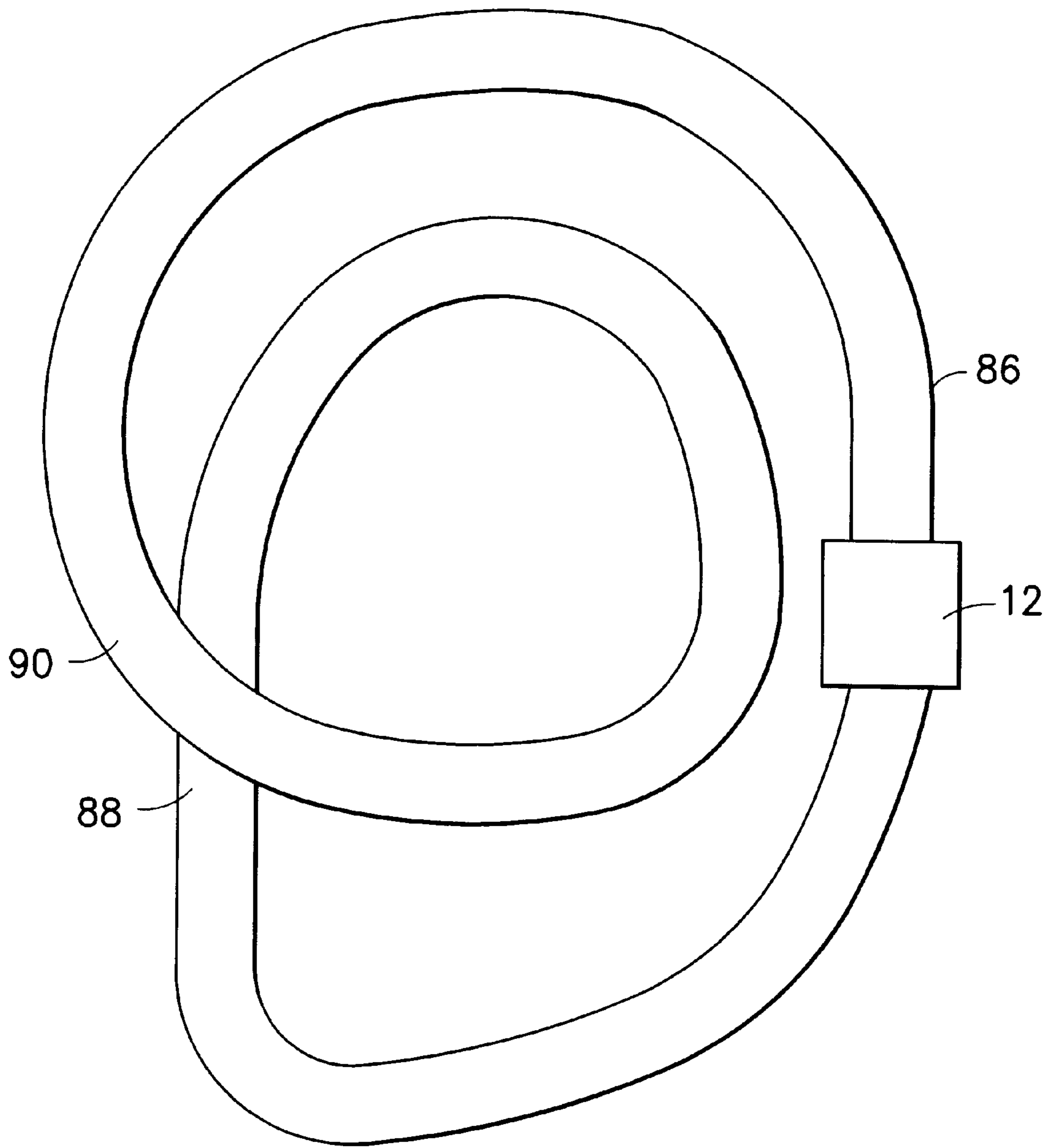
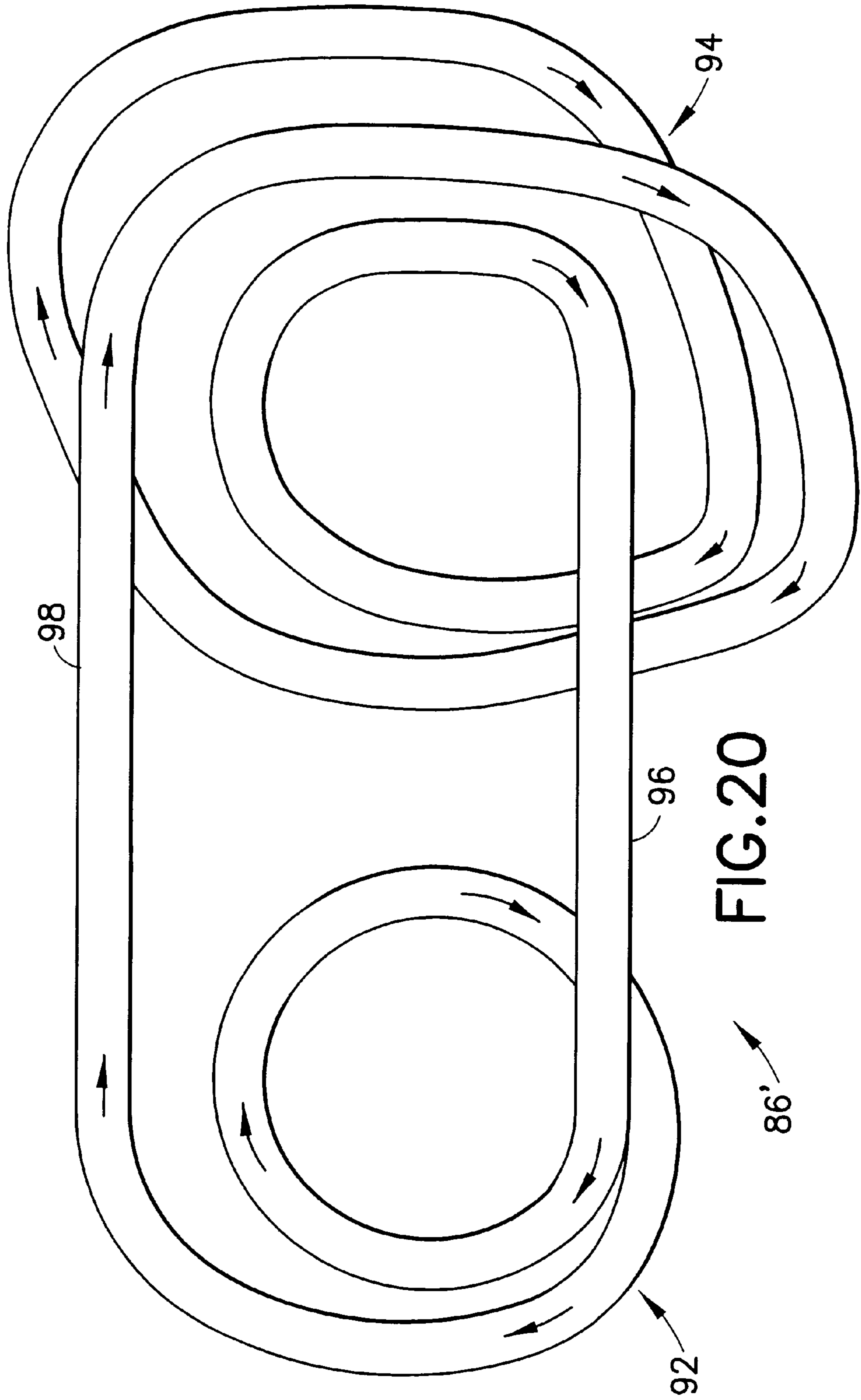


FIG. 19



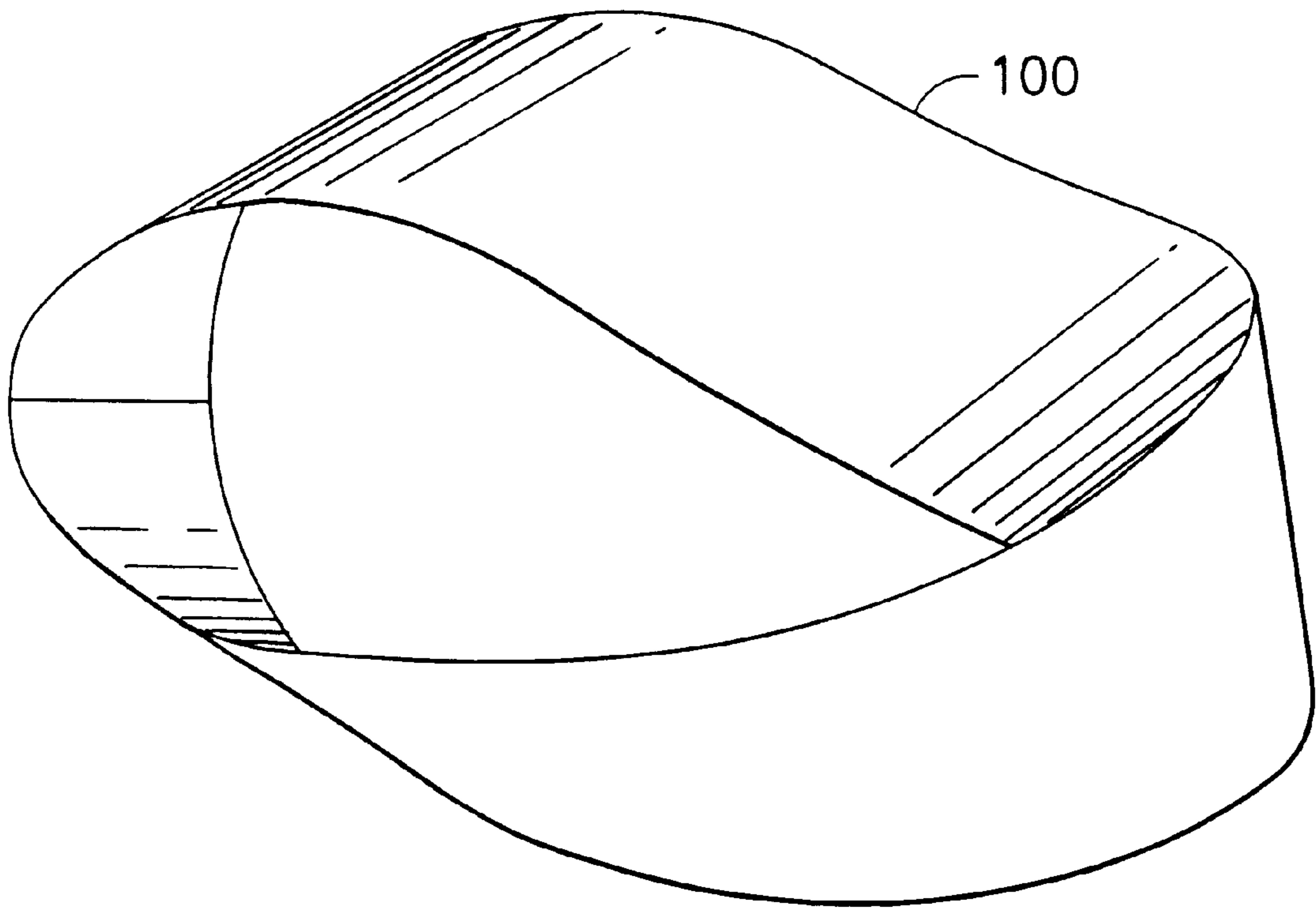


FIG.21

CLOSED-PATH LINEAR MOTOR

The present application is a continuation in part of U.S. patent application Ser. No. 09/031,009 entitled "LINEAR MOTOR HAVING AUTOMATIC ARMATURE WINDING SWITCHING AT MINIMUM CURRENT POINTS" filed Feb. 26, 1998; U.S. patent application Ser. No. 09/031,287 entitled "ENCODER" filed Feb. 26, 1998 now U.S. Pat. No. 5,907,200; U.S. patent application Ser. No. 09/040,132 entitled "MODULAR WIRELESS LINEAR MOTOR" filed Mar. 17, 1998; and U.S. patent application Ser. No. 09/055,573 entitled "WIRELESS PERMANENT MAGNET LINEAR MOTOR WITH MAGNETICALLY CONTROLLED ARMATURE SWITCHING AND MAGNETIC ENCODER" filed Apr. 6, 1998.

BACKGROUND OF THE INVENTION

The present invention relates to a linear motor and, more particularly, to a linear motor which is capable of following any path, including a closed path, where continuous or discontinuous motion in one direction is enabled.

Linear motors having stationary armatures containing coils and movable stages containing magnets are well known in the art. Also known are linear motors having stationary magnets and moving coils.

One type of such linear motors is disclosed in U.S. Pat. No. 4,749,921. The linear motor of the referenced disclosure has a series of armature windings mounted to a base plate, and a stage having a series of magnets that is free to move on the base plate. The stage is urged in the desired direction by applying AC or DC excitation to the coils. When such a linear motor is used in a positioning system, the relationship between the location of the stage and locations of the coils must be accounted for.

In one linear motor, commutator contacts are pendant from the stage. The contacts contact one or more power rails, and one or more coil contacts. As the stage moves along the armature, the location of the stage, relative to the armature is automatically accounted for by applying power to the stationary armature windings through the commutator contacts.

In other linear motors, it is conventional to employ a service loop of wires between the moving stage and the stationary elements. The location of the stage is updated using a magnetic or optical position encoder on the stage which senses markings on an encoder tape stationary alongside the path of the stage. The location is connected on the service loop to a stationary motor controller.

Generally, the important location information is the phase of the stage relative to the phase of the armature. For example, in a three-phase armature, the windings are disposed in repeating sets of three for phases A, B and C. If the center of the A phase winding is arbitrarily defined as 0 degrees, then the centers of the B and C windings are defined as 120 and 240. There may be two, three or more sets of windings as required for the travel distance of the stage. Normally, all A phase windings are connected in parallel. The same is true of all B and C phase windings. Thus, when the location of the stage requires a certain voltage configuration on the particular windings within the influence of the magnets on the stage, besides powering these windings, all of the other windings in the armature are also powered. The maximum force obtainable from a linear motor is limited by the allowable temperature rise in the armature windings. When all windings are powered, whether they contribute to motor force or not, more armature heating occurs than is strictly necessary for performing the motor functions.

Some linear motors in the prior art have responded to this heating problem using switches that are closed only to the armature windings actually within the influence of the magnets.

The need for a cable loop connecting moving and stationary elements is inconvenient, and limits the flexibility with which a system can be designed. The wiring harness requires additional clearance from the linear motor to prevent entanglement between the motor and any equipment or items that may be adjacent to the linear motor path. In addition, the wiring harness adds additional weight to the moving element of the linear motor. Furthermore, manufacturing of a linear motor employing a wiring harness incurs additional cost of material and assembly labor. Therefore, it would be desirable to eliminate the use of a wiring harness in a linear motor to decrease the cost of assembly, decrease the overall weight of the moving element, and to eliminate the clearance restrictions on the linear motors utility.

Most linear motors are manufactured to follow a straight path and to be of a predetermined fixed length. This establishes the length of the armature, and consequently the number of armature windings. In such linear motors, all armature windings lie parallel to each other, with axes thereof generally 90 degrees to the travel direction of the linear motor. In order to make a new linear motor of any specific length, a new assembly must be tooled. Each assembly has a set number of armature windings, a set number of moveable magnets, and, a fixed length wiring harness associated with the moveable element of the linear motor. The cost of producing a linear motor is increased because each assembly must be custom designed to a users needs, with new tooling required for each such design. Therefore, it is particularly desirable to produce a linear motor of a modular design.

A modular designed motor would allow easy customization for any desired length armature winding assembly. The cost of manufacturing a particular linear motor would be decreased since the cost of tooling would be minimal. A data base of assembly and outline drawings will be common to all assemblies within a family of linear motors, easing assembly and manufacturing. A stocking of common parts would allow quick assembly of any special length motor assembly, from now readily available parts. The stocking of common parts also decreases overall cost of manufacturing since materials will be bought in bulk from common suppliers. The assembly of any desired length armature winding assembly will enjoy a decreased lead time. As such, a modular designed linear motor provides for a decrease in manufacturing cost, decrease in lead time to assemble, and increases overall utility.

Linear motors using a series of stationary armature windings and moving magnets require a means to dissipate heat from the coils. Linear motors having cold plates mounted on one edge of an armature winding are known in the art. Alternatively, armature windings having cooling coils or channels are also well known in the art. Examples of such armatures are disclosed in U.S. Pat. No. 4,839,545. These armatures use stacked laminated magnetic material.

Linear motors having non-magnetic armatures are also known, an example of which is disclosed in U.S. Pat. No. 4,749,921. The linear motor of the referenced disclosure has a non-magnetic armature which includes a coil support structure composed of an aluminum frame or a serpentine cooling coil. In the embodiment having an aluminum frame, heat is carried away from the coils of the armature via the aluminum frame and a side plate which functions as a heat

sink. Alternatively, a serpentine coil may be employed to effect more uniform cooling within the armature. The serpentine coils support the overlapping coils while the coils and the armature are cast in a block of settable resin. However, the incorporation of such a coil has the disadvantage of increasing costs because of the complexity of assembly and material expenses. Furthermore, while the use of the settable resin prevents the occurrence of eddy currents, the thermal conductivity of the settable resin is significantly less than that of metals which it replaces and thus reduces the power dissipation capacity of the linear motor.

Linear motors are increasingly being employed in manufacturing equipment. In such equipment, nominal increases in the speed of operation translate into significant savings in the cost of production. Therefore, it is particularly desirable to produce as much force and acceleration as possible in a given linear motor. An increase in force generated requires either an increase in magnetic field intensity or an increase in current applied to coils of the armature. In a permanent magnet linear motor, the available magnetic field intensity is limited by the field strength of available motor magnets. Power dissipated in the coils increases at a rate equal the square of the current. Attendant heat generation limits the force that may be achieved without exceeding the maximum armature temperature. Therefore, improvements in the power dissipation capacity of linear motors provide for increases in their utility.

OBJECTS AND SUMMARY OF THE INVENTION

Accordingly, it is an object of the invention to provide a linear motor which overcomes the drawbacks of the prior art.

It is a further object of the invention to provide a linear motor that is capable of traversing any desired path, including a closed path.

It is a still further object of the invention to provide a wireless linear motor that eliminates the need for a wiring harness, thereby permitting the linear motor to operate over a path which is closed on itself.

Briefly stated the present invention provides a linear motorpath that forms a closed figure. Contactless power control and position feedback permit a linear motor stage to traverse the closed figure without interference from trailing wires. One embodiment of the closed figure includes a racetrack pattern with straight runs joined by curved ends. Axes of armature windings are skewed to lie across the path in the curved ends to maintain force on the linear motor stage. Other embodiments of the invention includes multi-level paths wherein one portion of the path crosses over another portion of the path. Disclosure is made of a linear motor stage supported below the path by magnetic attraction between permanent magnets on the stage and magnetic material in the path.

According to an embodiment of the invention, there is provided a linear motor comprising: a path, the path including a plurality of armature windings therein, a plurality of switches, each one of the switches controlling application of power to one of the armature windings, a linear motor stage movable on the path, a plurality of motor permanent magnets on the stage facing the path for interaction with the armature windings, means for controlling actuation only of those of the switches controlling application of power to those of the plurality of armature windings within a magnetic influence of the motor permanent magnets, the path describing a closed path, and means for permitting the linear motor stage to traverse the closed path.

According to a feature of the invention, there is provided a path for a linear motor comprising: a plurality of armature windings in the path, means for controlling application of power to the plurality of armature windings, and the path including at least first and second levels.

According to a further feature of the invention, there is provided a linear motor comprising: a path, the path including a magnetic material therein, a movable stage movable on the path, the movable stage including permanent magnets thereon facing the magnetic material, at least a portion of the path placing the movable stage below the path, and the permanent magnets having sufficient magnetic attraction to the magnetic material to retain the movable stage on the path, including the at least a portion.

The above, and other objects, features and advantages of the present invention will become apparent from the following description read in conjunction with the accompanying drawings, in which like reference numerals designate the same elements.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a simplified schematic diagram linear motor system according to an embodiment of the invention.

FIG. 1B is a transverse cross section taken along II—II in FIG. 1.

FIG. 2 is a cross section taken along A—A in FIG. 1B, showing the switching magnet and switching sensors which control application of drive power to armature windings.

FIG. 3 is a cross section taken along C—C in FIG. 1B, showing the relationship between the switching magnet and motor magnets.

FIG. 3A is a cross section taken along C—C in FIG. 1B, showing, the positional relationship between the switching magnets and the motor magnets.

FIG. 3B is a cross section taken along C—C as in FIG. 3A, where the movable stage has moved to the right from its position in FIG. 3A.

FIG. 4 is cross section taken along B—B in FIG. 1B showing the relationship between magnetic zones in the encoder magnet and the encoder sensors.

FIG. 4A shows a shape of a beveled magnetic zone about one of the encoder sensors from FIG. 4.

FIG. 4B shows the relationship between the output of the encoder sensors located at the left and right ends of the encoder magnets in FIG. 4, and the beveled magnet zone in FIG. 4A.

FIG. 4C shows another shape of a beveled magnetic zone about one of the encoder sensors from FIG. 4.

FIG. 5 is a schematic diagram showing an embodiment of a wireless linear motor employing active communications elements on the movable stage.

FIG. 6 is a schematic diagram showing an embodiment a wireless linear motor employing an active command-response position feedback system.

FIG. 7 is a cross section similar to FIG. 1B, except that provision is made in the path for controlling a second movable stage along the same path.

FIG. 8 is a cross section similar to FIG. 1B, except that provision is made in the path for controlling any desired number of stages along the same path.

FIG. 9 is a cross section similar to FIG. 1B, except that provision is made in the path for controlling two or more stages along the same path.

FIG. 10 is a cross section similar to FIG. 1B, except that provision is made in the path for controlling three or more stages along the same path.

FIG. 11 is a schematic diagram of a wireless linear motor employing an active command-response system with memory on-board the movable stage.

FIG. 12 is a diagram showing a path adapted for open-loop control of a movable stage over one section and closed-loop control over another section.

FIG. 13 is a diagram showing several path modules connected together to form a path.

FIG. 14 is a diagram showing a preferred embodiment of a path module having three encoder sensor groups spaced along the path of the module.

FIG. 15 is a diagram showing an embodiment of two path modules coupled together, one module having a sensor, and another module without a sensor.

FIG. 16 is a diagram showing an alternative embodiment of a path module having a single sensor.

FIG. 17 is a diagram of a linear motor with a path in a racetrack shape.

FIG. 18 is an enlarged view of a portion of a curved section of the path of FIG. 17.

FIG. 19 is a diagram of a linear motor having path with multiple levels and wherein one portion of the path crosses over or under another portion of the path.

FIG. 20 is a diagram of a linear motor path consisting of two connected spirals, including multiple crossovers.

FIG. 21 is a diagram of a linear motor path in the shape of a Moebius band.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIG. 1A, there is shown, generally at 10, a linear motor according to the invention. A movable stage 12 is supported and guided in any convenient manner along a path 14. Path 14 includes therein repeating sets of three armature windings 16A, 16B and 16C for receiving, respectively, phases A, B and C of three-phase drive power produced by a motor controller 18. Phase A of the drive power from motor controller 18 is connected on a phase-A conductor 20A to terminals of normally-open phase-A switches 22A. Each phase-A switch is connected to its associated phase-A armature winding 16A. Similarly, phase-B and phase-C drive power are connected on phase-B and phase-C conductors 20B and 20C to terminals of phase-B and phase-C switches 22B and 22C, all respectively. Armature windings 16A, 16B and 16C of each set are noninterleaved. That is, they lie side by side, not overlapping as is the case in some prior art linear motors.

All switches 22A, 22B and 22C remain open, except the switches associated with the particular armature windings 16A, 16B and 16C that are within the influence of motor magnets on movable stage 12. The closed switches 22A, 22B and 22C that are closed in this manner are indicated as 22A', 22B' and 22C', thereby apply power to corresponding armature windings 16A', 16B' and 16C'. As moveable stage 12 moves along path 14, those of switches 22A, 22B and 22C which newly come under the influence of the magnets on movable stage 12 close, and those moving out of the influence of the magnets are opened. Thus, at any time, only the armature windings 16A', 16B' and 16C' which can contribute to generating a force on movable stage 12 are powered. The remainder of armature windings 16A, 16B and 16C, not being useful for contributing to the generation of force, remain in a quiescent, unpowered, condition. This contributes to a reduction in power consumption, and a corresponding reduction in heating compared to prior-art

devices in which all armature windings are powered, regardless of whether they are position to contribute to force.

In an application where "open-loop" drive of movable stage 12 is satisfactory, motor controller 18 produces the required sequence of phases to drive stage 12 in the desired direction. However, one desirable application is a "closed-loop" drive system in which motor controller 18 receives feedback information from movable stage 12 indicating either its position along path 14, or increments of motion along path 14. A closed-loop system permits accurate control of position, velocity and acceleration of movable stage 12.

The prior art satisfies the requirement for position feedback using wiring between movable stage 12 and motor controller 18. This is inconvenient in some applications, and impractical in others. Impractical applications including travel of movable stage 12 along a path 14 which is closed upon itself. An example of such a path is an oval or "race-track" pattern of value in a robotic assembly operation, to be described in greater detail later in this specification. That is, movable stage 12 continues in a forward direction repeatedly traveling in the same direction on path 14. Wiring between the movable and stationary elements for such an application is either difficult or impossible to accomplish.

The embodiment of the invention in FIG. 1A includes a communications device 24 which wirelessly informs motor controller 18 about the position and/or incremental motion of movable stage 12. Communications device 24 is preferably a linear encoder which does not require connecting cables between stationary and movable elements, as will be explained.

In the preferred embodiment, at least some of the position or motion information is developed at stationary locations off movable stage 12, without requiring the transmission of position information.

It can be seen from the simplified drawing of FIG. 1A, and the description above, that linear motor 10 requires the following actions:

- 1) control of switches 22A, 22B, 22C
- 2) feedback of position or motion data
- 3) drive power generation related to position (or motion-derived position).

Referring to FIG. 1B, a cross section through path 14, looking at the end of movable stage 12 reveals a plurality of motor magnets 160, 162 below a plate 26. Lower surfaces of motor magnets 160, 162 are maintained closely parallel to an upper surface of armature windings 16A, 16B and 16C. Although it does not form a part of the present invention, armature windings 16A, B, C, may be wound on stacked laminations of magnetic metal. In this case, the lower surface of motor magnets 160, 162 are maintained closely parallel to an upper surface of the stacked laminations. Some applications may benefit from the reduction in static load on movable stage 12 provided when armature windings 16A, 16B and 16C contain no magnetic material. For purposes of later description, motor magnets 160, 162 are referred to as motor magnets. Armature windings 16A, B and C are energized as necessary to interact with motor magnets 160, 162 whereby a translational force is generated on movable stage 12.

A pendant arm 28 extends downward from plate 26. Pendant arm 28 has attached thereto a switching magnet 30 and an encoder magnet 32, both movable with movable stage 12. A rail 34, affixed to path 14, rises generally parallel to pendant arm 28. Rail 34 has affixed thereto a plurality of

longitudinally spaced-apart switching sensors **36** facing switching magnet **30**, and a plurality of longitudinally spaced-apart encoder sensors **38** facing encoder magnet **32**.

Referring now to FIG. 2, switching sensors **36** are evenly spaced along rail **34**. Each switching sensor **36** is preferably positioned on rail **34** aligned with its respective armature winding **16**. In the embodiment shown, switching sensors **36** are Hall-effect devices. Switching magnet **30** has a length in the direction of travel roughly equal to the length of travel influenced by the magnetic fields of motor magnets **160**, **162**. This length is variable in dependence on the number of motor magnets used. In the illustrated embodiment, the length of switching magnet **30** is sufficient to influence nine switching sensors **36**. That is, nine armature windings **16** (three sets of phases A, B and C) are connected at any time to their respective power conductors **20** for magnetic interaction with motor magnets **160**, **162**.

Switching sensors **36** control the open and closed condition of respective switches, as previously explained. Any convenient type of switch may be used. In the preferred embodiment, the switches are conventional semiconductor switches such as thyristors. Since semiconductor switches, and the technique for controlling their open/closed condition are well known to those skilled in the art, a detailed description thereof is omitted.

Referring now to FIG. 3, the underside of plate **26** includes nine motor magnets **160** equally spaced therealong. In addition, an additional motor magnet **162** is disposed at each end of the array of nine motor magnets **160**. Motor magnets **160**, **162** are tilted as shown in a conventional fashion to reduce cogging. It will be noted that the length of switching magnet **30** is approximately equal to the center-to-center spacing of the end ones of the set of nine full motor magnets **160**. This length of switching magnet **30** defines the span **S** of the active portion of linear motor **10**. That is, only those of armature windings **16** that lie within the span **S** receive power. As armature windings **16** enter the span **S**, they receive power, as they exit the span **S**, power is cut off.

Additional motor magnets **162**, being outside the span, do not contribute to the generation of force because armature windings **16** below them are unpowered. However, additional motor magnets **162** perform an important function. It is important to the function of linear motor **10** that the magnetic field strength along plate **26** be generally sinusoidal. In the absence of additional motor magnets **162**, the magnetic fields produced by the two motor magnets **160** at the ends of span **S** depart substantially from sinusoidal due to fringing effects. This produces ripple in the force output. The presence of additional motor magnets **162**, by maintaining substantially sinusoidal magnetic field variations along motor magnets **160**, avoids this source of ripple.

Additional motor magnets **162** are shown with widths that are less than that of motor magnets **160**. It has been found that a narrower width in additional motor magnets **162** produces satisfactory results. However, it has also been found that a wider additional motor magnet **162** does not interfere with the function. From the standpoint of manufacturing economy, it may be desirable to employ only a single size magnet for both motor magnets **160** and additional motor magnets **162**, thereby reducing stocking costs, and assembly costs.

Referring now to FIG. 3A, the positional relationships of switching magnet **30** and motor magnets **160**, **162** are shown, using a reduced set of **5** motor magnets interacting with **4** armature windings, for purposes of explanation. As movable stage **12** moves, switching magnet and motor magnets **160**, **162** move together with it, maintaining the

same relative positions. As movable stage **12** moves along, those switching sensors **36** adjacent switching magnet **30** turn on their respective switches. Switching sensors **36** that are not adjacent switching magnet **30** maintain their respective switches turned off. In the condition shown, switching sensors **36** centered on armature windings **16-2**, **16-3**, and **16-4** are adjacent switching magnet **30**, and these armature windings are connected to drive power. The switching sensors **36** centered on armature windings **16-1**, **16-5** and **16-6** are not adjacent switching magnet **30**, and therefore, these switching sensors **36** maintain armature windings **16-1**, **16-5** and **16-6** cut off from drive power. The centers of all motor magnets **160** shown are offset from the centers of the armature windings **16** most closely adjacent. Therefore all turned-on armature windings **16** produce force by the interaction of their magnetic fields with the magnetic fields of the three nearest motor magnets **160**.

Referring now to FIG. 3B, movable stage **12** has moved to the right from its position in FIG. 3A until the center of the right-hand motor magnet **160** is centered over the center of armature winding **16-5**. In this relationship, the end of switching magnet **30** just reaches a position adjacent switching sensor **36**. This is a minimum-current position. Thus, at this instant, switching sensor **36** closes its switch to connect armature winding **16-5** to its power source. In this center-overlapped condition, armature winding **16-5** is incapable of generating a force. Thus, the current in armature winding **16-5** is at a minimum, and the switching takes place at minimum current to armature winding **16-5**. Similarly, at about this same instant, the left-hand end of switching magnet **30** passes off the switching sensor **36** aligned with armature winding **16-2**, thereby cutting off power to armature winding **16-2**. The center of left-hand motor magnet **160** is aligned with the center of armature winding **16-2** at this time. Thus, the current to armature winding **16-2** is minimum at this time. The above switching at minimum current reduces electrical switching noise which would be generated if switching were to take place at times when an energized armature winding **16** is generating force, or a deenergized armature winding **16** would generate a force immediately upon energization.

For a three-phase drive system, a minimum of five motor magnets is required to interact at any time with a minimum of four armature windings, or vice versa. If additional force is desired, magnets can be added in increments of four. That is, the number of magnets= $5+4L$ where **L** is an integer, including zero. The number of armature windings in span **S**=(number of motor magnets in span **S**)-1. The embodiment in FIGS. 2 and 3 employ $5+(4\times 1)=9$ magnets. The positioning of the magnets is such that the center-to-center spacing of the extreme ends of the **9** magnets is equal to the center-to-center spacing of **8** armature windings.

Referring now to FIG. 4, encoder magnet **32** includes alternating magnetic zones alternating with north and south polarities facing encoder sensors **38**. Accordingly, each encoder sensor **38** is exposed to alternating positive and negative magnetic fields as encoder magnet **32** passes it. The zones at the extreme ends of encoder magnet **32** are beveled magnetic zones **42**. Beveled magnetic zones **42** produce an increasing or decreasing magnetic field as it moves onto or off an encoder sensor **38**. Beveled magnetic zones **42** are illustrated as linear ramps. Motors using such linear ramps have been built and tested successfully. However, a shape other than a linear ramp may give improved results. It is known that the magnetic field of a motor magnet decreases as the square of the distance from the magnet. Thus, to have an increase in magnetic field at one beveled zone that is

substantially equal to the decrease in the magnetic field at the opposite magnetic zone, the bevel shape may be described by a squared law.

Referring momentarily to FIG. 4A, a shape of beveled magnetic zone which satisfies the rule that, for equal increments of motion of beveled magnetic zone 42', there are equal changes in magnetic field at encoder sensor 38 is represented by the equation:

$$y=a+bx^2$$

where:

y is the distance from the surface of the magnet to encoder sensor 38,

x is the position along beveled magnetic zone 42', and
a and b are constants.

Experience dictates that other factors besides the square law above affects the relationship between magnetic field and distance. The shape of beveled magnetic zones 42' may require modification from the square law to account for such other factors.

Referring now to FIG. 4B, when the ideal shape of beveled magnetic zones 42' is attained, the outputs of the encoder sensors at the left and right ends of encoder magnet 32 should approximate the figure. That is, the sum of the signal from the left beveled magnetic zone 42', and the signal from the right beveled magnetic zone 42' should remain about constant.

Returning now to FIG. 4, each encoder sensor 38 is preferably a Hall-effect device. A Hall-effect device produces a current when exposed to one magnetic polarity (north or south) but is insensitive to the opposite magnetic polarity. Encoder sensors 38 are disposed into encoder sensor groups 40 consisting of four encoder sensors 38 spaced in the direction of travel. Each encoder sensor group 40 is spaced from its neighboring encoder sensor group by a distance D. Distance D is seen to be equal to the center-to-center distance between the beveled magnetic zones 42 at the ends of encoder magnet 32. The four encoder sensors 38 in each encoder sensor group 40 are spaced in the direction of travel of movable stage 12 in relation to the center-to-center distance between magnetic zones in encoder magnet 32. For purposes of description, the center-to-center distance between magnetic zones of like polarity is considered to be 360°. Thus, the center-to-center distance between adjacent magnetic zones is considered to be 180°, and the distance between the center of a zone and its edge is considered to be 90°.

It is conventional for encoders to produce a sine and a cosine signal, relatively 90° out of phase, for use in detecting the direction of incremental motion of a stage. With magnetically actuated Hall-effect devices, this conventional technique presents a problem in that a Hall effect device responds only to one magnetic polarity (north or south) and is insensitive to the opposite polarity. To solve this problem, each encoder sensor group 40 includes one encoder sensor 38s+ for producing a sine+ output, and a second encoder sensor 38s- for producing a sine- output. Encoder sensor 38s- in encoder sensor group 40 is spaced 180° in the direction of travel from its companion encoder sensor 38s+. When the sine+ and sine- signals are added in motor controller 18, the desired sinusoidal sine signal is available. A cosine+ encoder sensor 38c+ is spaced 90° in the direction of travel from sine+ encoder sensor 38s+. A cosine- encoder sensor 38c- is spaced 180° in the direction of travel from its companion cosine+ encoder sensor 38c+. When the cosine+ and cosine- signals are added in motor controller 18, the desired cosine signal is generated.

The spacing D between encoder sensor groups 40 is such that, as a particular encoder sensor 38 in one encoder sensor group 40 is aligned with beveled magnetic zone 42 at one end of encoder magnet 32, its counterpart is aligned with beveled magnetic zone 42 at the opposite end of encoder magnet 32. As illustrated, for example, when sine+ encoder sensor 38s+ in the left-hand encoder sensor group 40 is aligned with the center of the left-hand beveled magnetic zone 42, its counterpart sine+ encoder sensor 38s+ is aligned with the right-hand beveled magnetic zone 42 at right end of encoder magnet 32.

All corresponding encoder sensors 38 are connected in parallel to a line connected to motor controller 18. Four separate lines are illustrated to carry the ±sine/cosine signals. As movable stage 12 moves along, the encoder sensor 38 coming into alignment with beveled magnetic zone 42 at one end of encoder magnet 32 produces an increasing signal while the encoder sensor 38 moving out of alignment with beveled magnetic zone 42 at that end produces a decreasing signal. Since all corresponding encoder sensor signals are added, the signal transition, as one encoder sensor group 40 becomes active, and its neighbor encoder sensor group 40 becomes inactive is smooth, without a discontinuity that would interfere with detecting motion. One skilled in the art will understand that the above spacing can be increased by 360° between any ± pair of encoder sensors 38 without affecting the resulting output signal. Also, in some applications, since the outputs of sine encoder sensors are, in theory, 180° out of phase with each other, both sine encoder outputs could be applied to a single conductor for connection to motor controller 18. In other applications, four separate conductors, as illustrated, may be desired.

In a preferred embodiment of linear motor 10, a third encoder sensor group 40 (not shown) is disposed midway between the illustrated encoder sensor groups 40. This has the advantage that, during the transition of beveled magnetic zones 42 at the ends of encoder magnet 32 from one encoder sensor group 40 to the next encoder sensor group 40, resulting departures of the encoder signal due to tolerances in the lengths of encoder magnet 32, and the precise spacing of encoder sensor groups 40 is at least partially swamped out by the signal generated by an encoder sensor group 40 located midway between the ends of encoder magnet 32.

Referring again to FIG. 1A, it will be recognized that the functions of communications device 24 are satisfied by the above-described wireless magnetic system for communicating the motion of movable stage 12 to motor controller, without requiring any active devices on movable stage 12. One limitation on such a system is the difficulty in producing closely spaced alternating magnetic zones in encoder magnet 32. Thus, the positional resolution of such a system is relatively crude.

Referring now to FIG. 5, one solution to the resolution problem includes a conventional encoder tape 44 in a fixed location along path 14, and a conventional optical encoder sensor 46 on movable stage 12. Encoder tape 44 is ruled with fine parallel lines. Optical encoder sensor 46 focuses one or more spots of light on encoder tape 44, and detects the changes in light reflected therefrom as lines and non-lines pass in front of it. Generally, optical encoder sensor 46 produces sine and cosine signals for determining motion. Since the parallel lines on encoder tape 44 are closely spaced, very fine resolution is possible. An optical encoder system can be added to the less precise magnetic encoder system in order to obtain enhanced position resolution.

The sine and cosine outputs of optical encoder sensor 46 are applied to a pulse generator 48. The output of pulse

generator **48** is applied to a transmitter **52**. Transmitter **52** transmits the pulse data to a data receiver **54**. Although the system is shown with antennas, implying that transmission and reception use radio frequency, in fact, any wireless transmission system may be used. This includes radio, optical (preferably infrared), and any other technique capable of transmitting the information, without requiring connecting wires, from movable stage **12** to stationary motor controller **18**.

The embodiment of the invention of FIG. **5** has the disadvantage that transmitter **52** is active at all times. Since the system is wireless, the illustrated apparatus on movable stage **12** is battery operated. Full-time operation of transmitter **52** reduces battery life.

Referring now to FIG. **6**, an embodiment of the invention adds to the embodiment of FIG. **5**, a command transmitter **56** in motor controller **18**, a receiver **58** and a counter **50** in movable stage **12**. In this embodiment, transmitter **52** remains off until commanded through receiver **58** to transmit the count stored in counter **50**. The command to transmit is sent from command transmitter **56** to receiver **58**. Although this embodiment requires that receiver **58** remain active at all times, the power drain of a solid state receiver is generally lower than that of a transmitter. As in prior embodiments, any wireless technology may be used in receiver **58** and command transmitter **56**.

In one embodiment of the invention, the magnetic encoder system may be omitted, and the entire encoder operation may be accomplished using optical encoder sensor **46** facing optical encoder tape **44**, and transmitting the position or motion data from the stage using electromagnetic means, such as described above.

Referring now to FIG. **7**, an embodiment of the invention is shown in which it is possible to drive more than one movable stage **12** along path **14**. Each movable stage **12** requires independent application of armature power from motor controller **18**, independent armature switching and independent position communication from the movable stage back to motor controller **18**. The embodiment in FIG. **7** continues to show movable stage **12**, but adds a second rail **34'** on the second side of path **14** for use by a second movable stage (not shown). The second movable stage is similar to movable stage **12**, except that a pendant arm **28'** (not shown), supporting switching and encoder magnets (not shown), if in a visible position, would be located on the left side of the drawing. Second rail **34'** includes encoder sensors **38'** and switching sensors **36'**, corresponding to the encoder and switching sensors of the embodiment of FIG. **1B**. Conductors **20'A, B** and **C** carry motor drive power, separately generated in motor controller **18**, to the switches feeding power to the armature windings **16A, B** and **C**, along paths separate from conductors **20A, B** and **C**. In this manner, the second stage is separately controlled, and its motion is separately fed back to motor controller **18**.

Referring now to FIG. **8**, there is shown an embodiment of the invention adapted to controlling and driving two movable stages **12** (and **12'**, not shown). In this embodiment, rail **34'**, besides supporting encoder sensor **38** and switching sensor **36**, also supports, spaced below, a second encoder sensor **38'** and a second switching sensor **36'**. It will be understood power to armature windings **16A, B** and **C** is independently controlled by separate switches that feed motor power from conductors **20A, B** and **C**, when influenced by switching magnet **30**, and from conductors **20'A, B** and **C** when influenced by switching magnet **30'**.

Referring to FIG. **9**, a second movable stage **12'** is shown, for use with rail **34'** of FIG. **8**. Second movable stage **12'**

includes a pendant arm **28'**, on the same side of movable stage **12** of FIG. **8**, but extending further downward to accommodate an encoder magnet **32'** and switching magnet **30'** aligned with second encoder sensors **38'** and second switching sensors **36'**, respectively. It would be clear to one skilled in the art that more than two movable stages could be controlled by adding additional elements to rail **34'**, and by installing suitably long pendant arms **28, 28' . . . 28''** to each movable stage **12**.

The present invention is not limited to two movable stages on a single path. Any number of movable stages may be controlled independently along the same path **14**. Referring to FIG. **10**, for example, three rails **34, 34'** and **34''** are spaced parallel to each other outward from path **14**. Each of rails **34, 34'** and **34''** includes thereon encoder sensors **38, 38'** and **38''**, and switching sensors **36, 36'** and **36''**. Each movable stage **12, 12'** and **12''** (only movable stage **12** is shown) includes a pendant arm **28, 28'** and **28''** (only pendant arm **28** is shown) adjacent to the sensors on its respective rail **34, etc.** Encoder magnets **32, 32'** and **32''** (only encoder magnet **32** is shown), and switching magnets **30, 30'** and **30''** (only switching magnet **30** is shown) are installed on their respective pendant arms. With the interleaving of pendant arms **28, etc.** between rails **34, etc.**, as many stages **12, etc.** as desired may be accommodated, driven and controlled on a single path **14**.

In some applications, it may be desirable to have closed-loop control in some regions of the path for precise positioning, but where open-loop control may be desirable over other regions of the path. Referring to FIG. **12**, a region of closed-loop control **60**, along path **14** receives drive power from motor controller **18** on a first set of conductors **20A, B, and C** through magnetically actuated switches **22A, B** and **C**, as previously described. Position or motion feedback in region **60**, as previously described, permits motor controller **18** to accurately control the position and velocity of movable stage **12**. A region of open-loop control **62**, along path **14** receives drive power from motor controller **18** on a second set of conductors **20'A, B** and **C**. When movable stage **12** is in region **62**, motion feedback is either not generated, or is not responded to by motor controller **18**. Instead, motor controller **18** generates a programmed phase sequence for open-loop control of movable stage **12**. This drives movable stage at a predetermined speed. Once a region of closed-loop control is attained, movable stage **12** resumes operation under control of motor controller **18**.

It is also possible to provide path switching, similar to the switching used on railroads, to direct movable stage **12** flexibly along different paths.

Referring now to FIG. **11**, an embodiment, similar to that of FIG. **6**, adds a memory **64** for receiving commanded motion information. Once commanded motion information is stored, it is continuously compared with the content of counter **50** until a commanded condition is attained. During the interval between storage of the information, and the accomplishment of the commanded condition, transmitter **52** may remain quiescent. In some applications, receiver **58** may also remain quiescent during such interval, thereby consuming a minimum amount of battery power.

Referring now to FIG. **13**, the power consumption of the above-described system is independent of the length of path **14**, since only active armature windings **16** are energized. Consequently, it is convenient to be able to construct a path **14** of any length by simply adding path modules **66** end to end. Each path module **66** includes at least one armature winding **16**, an associated portion of rail **34** and conductors **20A, B** and **C**. Conductors **20A, B** and **C** on adjacent path

modules are connected together by connectors 68. Path modules 66 are illustrated to contain three armature windings 16A, B and C. It will be understood that switching sensors, together with their semiconductor switches, for the contained armature windings are mounted on the portion of rail 34 associated with that path module 66. In addition, position feedback, if magnetic encoder sensing is used, is also included on suitable path modules 66. As noted above, encoder sensors are spaced relatively widely apart. In a preferred embodiment, each path module should be long enough to contain at least one encoder sensor group. One system of this sort has been long enough to contain 9 armature windings (3 repetitions of phases A, B and C armatures).

Referring now to FIG. 14, a preferred embodiment of a path module 70 includes armature windings, as described above, plus three encoder sensor groups 40 spaced $D/2$ apart (D is the center-to-center spacing of beveled magnetic zones 42 at the ends of encoder magnet 32). Path module 70 extends a distance $D/4$ beyond the outer encoder sensor groups 40. In this way, when the next path module 70 is connected end to end, the distance between the nearest encoder sensor groups 40 on the mated path modules 70 is $D/2$ as is desired. Path modules 70 are connected together to form a path 14' of any desired length or shape.

Referring now to FIG. 15, another preferred embodiment includes two path modules 72, 74 having armature windings, as described above. One module has an encoder sensor group 40, and another module does not contain an encoder sensor. Path modules 72, 74 are connected together to form a path 14'' such that encoder sensor groups 40 in path modules 72 are spaced $D/2$ apart (D is the center-to-center spacing of beveled magnetic zones 42 at the ends of encoder magnet 32). Any desired path 14'' can be achieved using a combination of path modules 72 and 74. It is understood by one skilled in the art that other arrangements of path modules 72, 74 can be used to form any desired shape or length path 14'' and any other desired spacing of encoder sensor groups 40, so long as provision is made for spacing encoder sensor groups 40 a desired repeating distance apart. One embodiment includes a modular path module from which encoder sensor groups are omitted. However, provision is made for clamping, or otherwise affixing, encoder sensor groups 40 anywhere along the assembled modular path. When affixing the encoder sensor groups 40, the appropriate spacing (D , $D/2$, $D/4$, etc.) is observed to ensure that the encoding signal is produced without distortion or dropouts during transitions from one path module to another.

Referring now to FIG. 16, an alternative embodiment of a path module 76 includes armature windings, as described above, and an encoder sensor group 40. Modules 76 are connected together to form a path 14''' such that encoder sensor groups 40 in path modules 76 are spaced $D/2$ apart (D is the center-to-center spacing of beveled magnetic zones 42 at the ends of encoder magnet 32). Any desired length or shape path 14''' can be achieved using a combination of path modules 76.

The connection of signals and power along linear motor 10, especially in the case of modular devices, has been described with wires and connectors joining wires in adjacent modules. Other techniques for carrying signals and power may be employed without departing from the spirit and scope of the invention. For example, instead of using wires, conductive traces on a rigid or flexible substrate may be used.

It will be noted that path 14 is shown as containing curves. It is a feature of the present invention that path 14 is not

restricted to a straight line, as is frequently the case with the prior art. Instead, due to the nature of the present invention, linear motor 10 can be arranged to follow any desired path, including a straight path, curved path 14 as shown, or a closed path wherein movable stage 12 can repeatedly trace a closed path, moving in a single direction, or moving back and forth to desired locations anywhere along the open or closed path.

Referring now to FIG. 17, a linear motor 10' includes a path 14' which is closed on itself in a racetrack pattern. That is, path 14' includes straight and parallel runs 78 joined by curved ends 80. Movable stage 12 is driven, as described to any point on path 14'. In the preferred embodiment, movable stage 12 may continue in one direction indefinitely, or may move in one direction, then in the other, without limitation. This freedom of movement is enabled by the wireless control and feedback described herein.

Dashed box 82 in FIG. 17 is expanded in FIG. 18 to enable description.

All armature windings 16A, 16B and 16C include an axis 84, illustrated by a line in each armature winding. All axes 84 in runs 78 lie substantially parallel to each other, as shown in armature windings 16A and 16B at the lower left of the figure. Axes 84 in curved ends 80, however, do not lie parallel to each other. Instead, axes 84 in curved ends 80 are tilted with respect to each other so that they lie across the shortest transverse distance of path 14'. In this way, repeating sets of armature windings 16A, 16B and 16C are enabled to generate the desired force for urging movable stage 12 along path 14'.

One skilled in the art will recognize that accommodation must be made in the actuation times of switches 22A, 22B and 22C for the tilting of axes 84 in curved ends 80. One possibility includes adjusting an upstream-downstream dimension of armature windings 16A, 16B and 16C so that center-to-center dimensions between end ones of each set of four such windings in curved ends 80 remains the same as the center-to-center dimensions between corresponding windings in runs 78. In this manner, the span S of four armature windings 16 remains the same in curved ends 80 as the span S of $5+(n \times 4)$ motor magnets 160 ($n=0, 1, 2, \dots$) in straight runs 78. Switching sensors 36 are located along curved ends 80 so that their respective switches are actuated at minimum-current times, as previously explained.

A racetrack shape, as in FIGS. 17 and 18 do not exhaust the possible shapes of path that can be attained with the present invention. Any shape can be accommodated.

Referring now to FIG. 19, a multilevel path 86 is equally within the contemplation of the present invention. A lower portion 88 of path 86 passes under an upper portion 90, thereof. Movable stage 12 may be positioned anywhere on path 86. In cases where two or more movable stages 12 are employed on path 86, the possibility exists that one movable stage 12 may cross on upper portion 90 at the same time that a second movable stage 12 on lower portion 88 passes under upper portion 90.

Referring now to FIG. 20, a further illustration of a multilevel path 86' includes a down spiral 92 aside a down and up spiral 94. Spirals 92 and 94 are connected into a single path 86' by crossing elements 96 and 98. Spiral paths are frequently seen in conveyor systems to increase the residence time of objects in a location. For example, in a bakery operation, spirals are frequently used to permit time for newly baked goods to cool, before being discharged to packaging or further processing.

To illustrate the complete flexibility of the present invention, a path may be laid out as a Moebius band 100, as

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shown in FIG. 21. A Moebius band is characterized as having only a single edge and a single surface, rather than having two edges and two surfaces, as in other examples of paths in the above description. A toy Moebius band is constructed by making a half twist in a strip of paper and then connecting the ends together. One proves that the strip has only a single surface by drawing a line down the center of the strip. Eventually, the end of the line meets the beginning of the line without having turned the strip over. Similarly, one can draw a line along the edge of the strip, and find the end of the line joining the beginning of the line, without crossing over from one edge to the other, since the strip has only a single edge.

The views of paths in the foregoing must not be considered to be top views. Indeed, important applications of the invention include those in which movable stage 12 is located below its path. Especially in the case where the path includes magnetic material, motor magnets 160, and additional magnets 162 in movable stage 12 may be relied on to support movable stage by magnetic attraction to the magnetic material in the path. Other types of support are equally within the contemplation of the invention. In some cases, some portions of the path may be below and supporting movable stage 12, and other portions of the path may be above movable stage 12, as movable stage completes a full traverse of the path.

Having described preferred embodiments of the invention with reference to the accompanying drawings, it is to be understood that the invention is not limited to those precise embodiments, and that various changes and modifications may be effected therein by one skilled in the art without departing from the scope or spirit of the invention as defined in the appended claims.

What is claimed is:

1. A linear motor comprising:
 - a path;
 - said path including a plurality of armature windings therein;
 - a plurality of switches, each one of said switches controlling application of power to one of said armature windings;
 - a linear motor stage movable on said path;
 - a plurality of motor permanent magnets on said stage facing said path for interaction with said armature windings;
- means for controlling actuation only of those of said switches controlling application of power to those of

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said plurality of armature windings within a magnetic influence of said motor permanent magnets;

said path describing a closed path; and

means for permitting said linear motor stage to traverse said closed path.

2. A linear motor according to claim 1, wherein said means for permitting includes a contactless system for controlling the application of power to said armature windings.

3. A linear motor according to claim 2, wherein said means for permitting further includes contactless means for producing at least one of position and motion feedback from said movable stage.

4. A linear motor according to claim 1, wherein:

said closed path includes at least one curved portion;

each of said armature windings includes an axis;

at least some of said axes of said armature windings in said at least one curved portion are skewed with respect to axes of neighboring armature windings across said path; and

a skew of said axes being across a local width of said path.

5. A path for a linear motor comprising:

a plurality of armature windings in said path;

means for controlling application of power to said plurality of armature windings; and

said path including at least first and second levels.

6. A path according to claim 5 wherein said first level includes an upper portion which crosses over a lower level in said second level.

7. A path according to claim 6, wherein said first and second levels are joined to form a closed pattern.

8. A linear motor comprising:

a path;

said path including a magnetic material therein;

a movable stage movable on said path;

said movable stage including permanent magnets thereon facing said magnetic material;

at least a portion of said path placing said movable stage below said path; and

said permanent magnets having sufficient magnetic attraction to said magnetic material to retain said movable stage on said path, including said at least a portion.

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